Economic Impact of Bridge Damage in A Flood Event

A thesis submitted in fulfilment of the requirements for the degree of Master by Research

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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ABSTRACT

Bridges are vulnerable road infrastructure in flood events. Different level damage of bridge can be observed after flood events. As lifeline structures, bridge plays an important role in any road network. Bridge structures involve both great construction costs and great economic value to stakeholders. Despite costs for post-disaster clearance and repair of bridge structures, a decrease in the accessibility of bridges would have a significant impact on regional traffic, residents and businesses. Current knowledge still has gap on fully recognizing and understanding economic impacts of bridge damage. In addition, there was a lack of accurate, detailed and sufficient data as well as validated model that could be used to estimate all types of economic impacts. This research would base on a critical review of existing literature to solve two problems of understanding economic impacts of bridge damage:

What are the economic impacts of bridge damage in flood events? How to categorize these economic impacts systematically?

How can these economic losses be measured?

An in-depth understanding of the effects of bridge damage is required in order to develop estimation methods as well as sustainable management and adaptation strategies.

This research reviews and summarizes current knowledge on consequences that can be caused by bridge damage due to flood events. Each consequence is discussed and analysed. Likewise, this study systematically categorizes different types of potential economic impacts to bridge stakeholders and local councils into direct tangible/intangible and indirect tangible/intangible types.

In terms of measuring different types of economic impacts, it is still a great challenge due to the present knowledge gap. This research introduces and integrates existing models in different areas to measure economic impacts that are resulted from bridge damages. For the economic losses of bridge damage and recovery, this research discusses damage states, repair quantities, repair methods and repair costs, which provides guides for the stakeholders to predict repair costs and time limits of recovery projects. For the economic losses of bridge accessibility, this research concerns indirect tangible economic impacts, which include the detour of bridge users and the business interruption. In terms of detour costs of bridge users,

models prefer to use regional road networks, average local vehicle operating costs, post-disaster traffic conditions and alternative path choice to estimate the costs of the extra traveling and the opportunity costs of the extra traveling time. With regards to business interruption, this research measures business interruption and the decrease of productive capacity due to bridge damage.

Although most economic losses can be estimated by monetary flow, some types of economic losses need to be measured or interpreted in terms of consumption of social resources after bridge damage. This research also makes efforts to understand these economic impacts, such as the value of a historical bridge, impacts on the labour market change and losing the trust of authority.

To illustrate the application of integrating models, Kapernicks Bridge, which is located in Queensland and continues to be damaged as a result of floods in the Lockyer Valley region, is introduced as a case study in this research. In this case study, economic impacts that are summarized are discussed and estimated by the integrated model. In this part, estimation focuses on the costs of extra travel and the opportunity costs of extra travel time. This case study makes two main contributions. First of all, models apply regional data and figure out current data and knowledge gaps leading to model validation. Second, this case study can also be used as a guide to help stakeholders estimate their economic losses due to bridge damage after flood events. Therefore, a focused strategy can be made to decrease losses in the most disaster-affected region.

This research has two main contributions to current knowledge. The first one is its definition of economic impacts of bridge damage in a flood event. The second one is its application of existing knowledge and models to measure the majority of these economic impacts. Future research can focus on understanding the relations between damage states, repair methods, and repair quantities. Also, future research can make a contribution to knowledge of measuring losing trust on authorities.

ACKNOWLEDGEMENTS

This master program started in June 2014, when I decided to transfer to the construction school to continue my studies. I found research direction on natural disasters and their economic impacts when I browsed research projects in RMIT research programme. Since 1998, there have been lots of flood events and natural disasters reported by the press. I began to realize that these catastrophes created significant economic losses and brought pain to victims. When I discussed with Associated Professor Kevin Zhang about his project on the economic impacts of natural disasters and the resilience of the local community, he recommended research topics and supported me in conducting research on one part of the economic impacts of natural disasters. I would like to take part in and make a contribution to understanding the effects of natural disasters.

My research has been directed by Associated Professor Kevin Zhang. He provided a lot of help in this study. His supportive advice and critical comments guided this research. In the beginning, this research set too ambitious research topics and scopes that included as many economic impacts as I could review. He helps me to narrow down my research scope and set proper and attainable objectives. During research, my supervisor provided valuable suggestions and comments to help me to improve my research by introducing appropriate concepts and models. He organised weekly meetings to help me to identify components of economic impact, classification of economic impacts and introduce appropriate models.

Thanks to my associate supervisor Hessam Mohseni, who provides a lot of useful recommendations to help me improve my research. As one of the principals in the CRC project on economic impacts of road infrastructures that are damaged in natural disasters, he has comprehensive knowledge of road infrastructures. He guided me in identifying economic impacts and classifying economic impacts properly. To improve my knowledge of bridge damage in flood events and collect proper data, he contacted the local council to help me obtain post-disaster information. Also, he took me to Brisbane to gather information personally. I got a valuable chance to visit the local council to talk about post-disaster response and recovery. I also use this chance to check road networks around damaged bridges.

Also thanks to CRC (Cooperative Research Centres), who organised cooperative research work on the resilience of road infrastructure in flood events. I appreciate the encouragement and support from these organisations. It was my pleasure to have had the opportunity to join and make my contribution to this project. Also, this research got benefits from the cooperation works. CRC shared and provided important and valuable data that would be important to this research. The first and second report interpret concepts related to road infrastructure resilience, the importance of road infrastructure and impacts that are created by accessibility. These two reports summarized previous research and presented the findings from the interviews conducted with victims from flood-affected regions. All these types of information are a significant help to this study.

This researcher also appreciates the support of the Lockyer Valley local council. The local council provided the necessary data in detailed, including steel bracing drawings, bridge inspection reports conducted a year after bridge damage, and information about road network conditions and post-disaster traffic situations. Also, the local council shared some critical information on post-disaster conditions, which would help considerably in predicting post-disaster debris quantities, bridge repair, and recovery needs, post-disasters travel information, etc. Furthermore, the local council provided some valuable contact information to help me collect necessary information.

I enjoyed my time at RMIT. Thanks to the friendly staffs at RMIT. They provided assistance and support to me. Special thanks goes to my office mates, who helped me learn about English and Australian cultures. They offered kindness and friendship to me.

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YUE ZHANG

Contents

CHAPTER1 INTRODUCTION

1.1 Background

Road infrastructure throughout Australia is crucial to the Australian economy (Merick 2008). Road networks provide accessibility and support regional transportation. There is a direct correlation between growth in the demand for freight and passenger transport with growth in incomes (Economics 2007). With the increase in population and size of the economy, there is also growth of traffic demand in Australia. The primary value of roads to the local community can be interpreted as accessibility which assures social connection, business production, and the collective action. It connects employees with places of work, people with leisure activities, resources with centres of production, products with markets and consumers, etc (Merick 2008). Also, other types of infrastructure facilities rely on road infrastructures, for example, sewer, power, water, the internet, etc. Road in the most important lifeline in Australia.

In a road network, the bridge is a critical component (Padgett et al. 2008). It always connects two road networks or provides traffic diversion that can reduce traffic congestion, travel time and distance (Gentle, Kierce & Nitz 2001; Hallegatte & Przyluski 2010). Bridge value can be described as two parts: The first part is decided by its construction cost, which is also called assets value. In general, the construction of bridges involve great costs. For example, the Yeppen South project would cost 256 million AUD (Figure 1.1). The second part is the economic value of accessibility that is provided to stakeholders. Bridge closures will isolate two connected road networks. Disruption at the bridge can separate some rural areas accidently in some extreme conditions. According to a 2010 research report, the economic value of a bridge is much larger than its assets value, and the adverse effects on the local community cannot be easily measured in monetary terms (Hallegatte & Przyluski 2010).

Figure 1.1 Yeppen Bridge in Queensland (Ahmad 2006)

During the life cycle of bridges, the main threats are due to natural hazards. Natural hazards have the potential capacity to destroy both the physical body and accessibility of the bridge. Despite repairing the damaged physical body of the bridge after flood events, there are some potential losses due to decreasing bridge accessibility. Reduced accessibility means the disruption of traffic, leading to regular daily objectives, such as work, school, food, fuel, medical consultants, entertainment are not reachable or lack approaches (Greenberg, Lahr & Mantell). Also, accessibility is critical to the resilience of the local community. Loss of accessibility can lead to a delay in post-disaster rehabilitation after flood events. Rehabilitation of associated facilities, such as power, sewer, and the internet often rely on the bridges and other types of road infrastructure.

As a flood-vulnerable country, Australia has suffered from flood events (Guha-Sapir et al. 2011). There were 26 main flood events from January 2000 to July 2015. The expenditures that were calculated by the insurance companies for rehabilitation after disasters amounted to

4,329.5 million AUD (Australian Institute of Disaster Resilience 2015). In these flood events, lots of bridges were damaged or destroyed. According to a report from the Queensland government, critical road networks were damaged in almost every flood event (Repo 2012). In 2013, forty-two bridges were damaged in the Lockyer Valley region in Queensland. The economic costs of bridge damage are hard to predict. The figure that is calculated by the insurance company can not adequately reflect economic losses of bridge damage in flood events, as they only calculate properties that are covered by their insurance clauses.

1.2 Flood as one of the main threats to bridge

A flood event is one of the main threats that can affect the health and condition of road infrastructure most negatively (Hughes 2003; Koetse & Rietveld 2009). Australia is a flood-vulnerable country. The majority of bridges are threatened by risks of exposure and damage due to flood events. Australian has acquired the experience to improve the resilience of critical infrastructure after disaster events (Croope & McNeil 2011). However, the destruction of critical road networks still happens in almost every flood event in Queensland (Repo 2012). It has been investigated in post-disaster reports in Australia that many road structures have been affected by floods in flood-prone areas such as Queensland. However, in light of climate change and the population growth in Australia, the frequency, intensity, and the impacts of floods will increase.

1.2.1 More flood events in the near future

In Australia, flood events are high-frequency natural disasters. As one of the most catastrophic natural disasters, the flood can cause severe damage to road infrastructure. According to the report, heatwaves and flood events are considered to be natural hazards which will damage the road infrastructure the most (Hughes 2003). In this research, the damage caused by flood is the primary concern. A flood event is defined byGeoscience Australia as “a general and temporary condition of partial or complete inundation of normally dry land areas from overflow of inland or tidal waters from the unusual and rapid accumulation or runoff of surface waters from any source” (Australian Government of Geoscience Australia 2016). The causes of flood events are various. Floods can originate from the sea (coastal floods), from rivers (fluvial floods), from heavy rain events (pluvial floods) or from below the surface (groundwater floods) (Klijn 2009). Floods are widely distributed throughout all the large population areas in the Australia (Figure 1.2). The average annual direct cost of floods has been estimated at AUD370 million (BITRE 2008). The rainy season and tsunami bring floods almost every year around the coastal area. The increasing flood events will have implications for the bridges. According to the EM-DAT, there were forty-two severe floods recorded from 1990 to 2015, nearly 2.8 flood events on average per year. These flood events led to the death of 117 people, 89 injured, and 292939 people affected people (EM-DAT Database 2009).

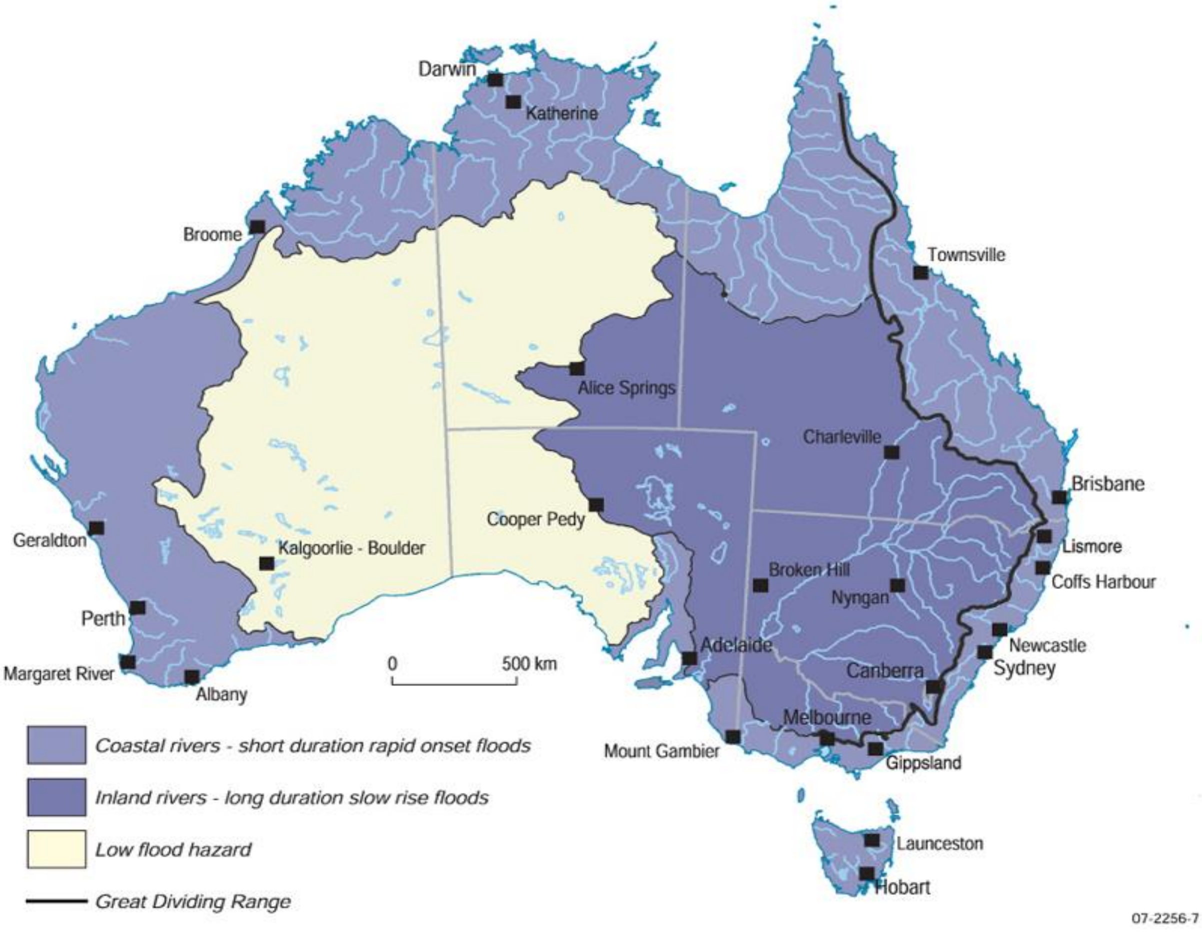


Figure 1.2 The distribution of flood events in Australia(Australian Government of Geoscience Australia)

The climate report claims that Australia will suffer more flood and extreme weather events shortly (Guha-Sapir et al. 2011; Hughes 2003). The increasing intensity and frequency of natural disasters, which are created by climate change, are pessimistic to road infrastructure and increase the possibilities of losses in these natural disasters (Bankoff, Frerks & Hilhorst 2004). Extreme events, especially bush fires, heat waves and floods, will increase in both frequency and intensity (Hughes 2003). Though the climate will become drier in Australia, the heavy storm and flood event will happen more frequently because of the extreme temperature change. Table 1.1 shows the increasing flood events in the recent two decades (EM-DAT Database 2009). Specifically, the most noticeable change is that the average extreme hot day is increasing, and the eastern part of Australia will become dryer while the western part of Australia will suffer more very heavy rain. It seems that the road infrastructure will be exposed to more risks from storms and flood events in the near future.

Table 1.1 Statistics of flood events

Time period	Number of flood events
1976-1985	9
1986-1995	8
1996-2005	22
2006-2015	17

Another reason that will lead to more flood events is that the increasing sea levels will increase the risks of exposing cities to a tsunami, rainstorm, and high tide events. The sea level has already increased 20- 60cm above the 1990 levels due to the global warming and they will continually increase (Guha-Sapir & Hoyois 2014). The direct effect is that the fringe part of the continent will be submerged. Some buildings and road infrastructures will become vulnerable. The straight line distances between the coastal cities and the coastline have also become shorter, which will exacerbate the adverse effects of ocean disasters.

1.2.2 Distribution of cities and flood events

In Australia, the majority of the cities and populations located around coastal lines. According to the population distribution research, the majority of Australians live within 50 KM of the coast (Hugo 2003) (Figure 1.3). Similarly, road infrastructure and support facilities are more intensive in high population density regions (Figure 1.4). Road infrastructure seems easily impacted by extreme coastal weather. According to the Bureau of Meteorology (BOM) Australia 2011, dynamic river flood maps (Figure 1.5) are quite similar to the allocation of road networks. It is evident that road infrastructure suffered in almost all flood events in the past. Bridges, as part of the road network, are also exposed to flood events.

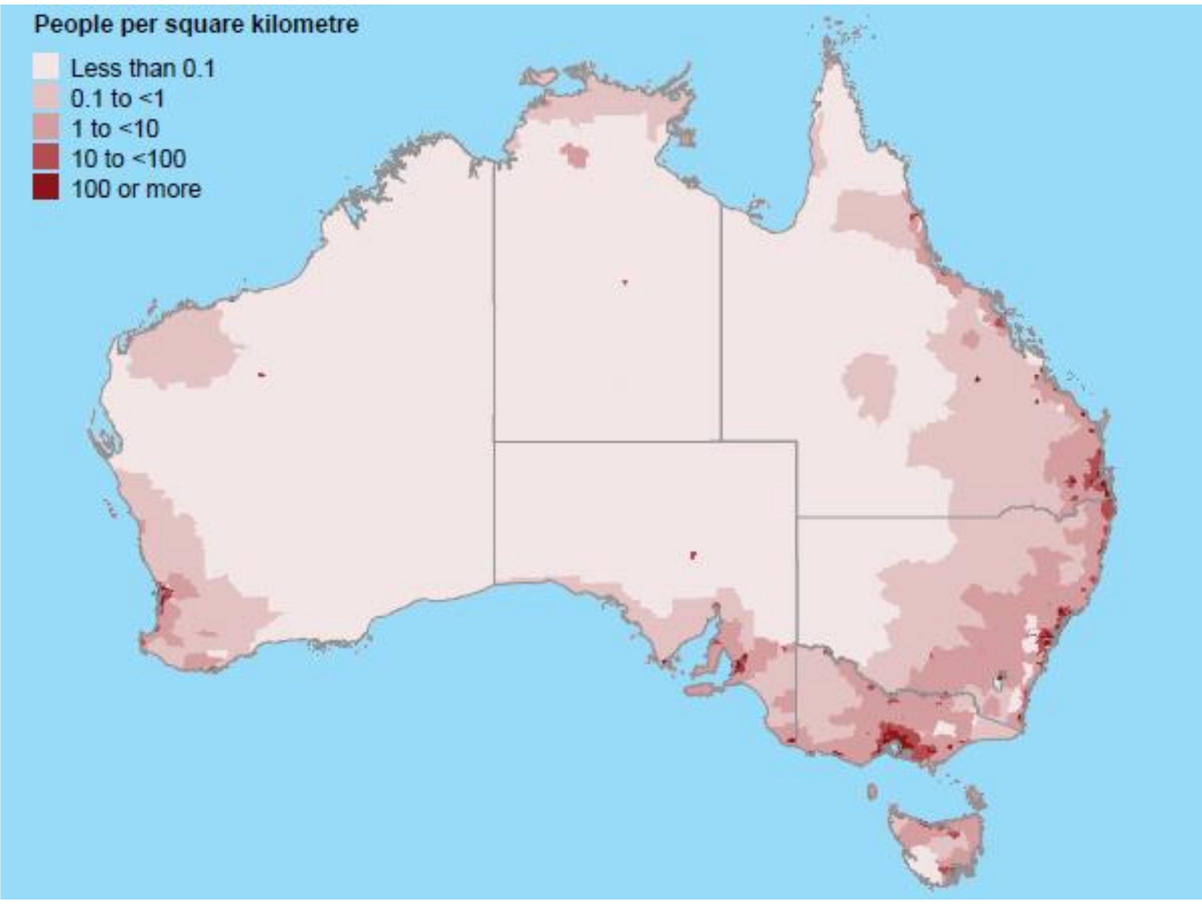


Figure 1.3 Cities distribution of Australia(ABS 2010a July 2011)

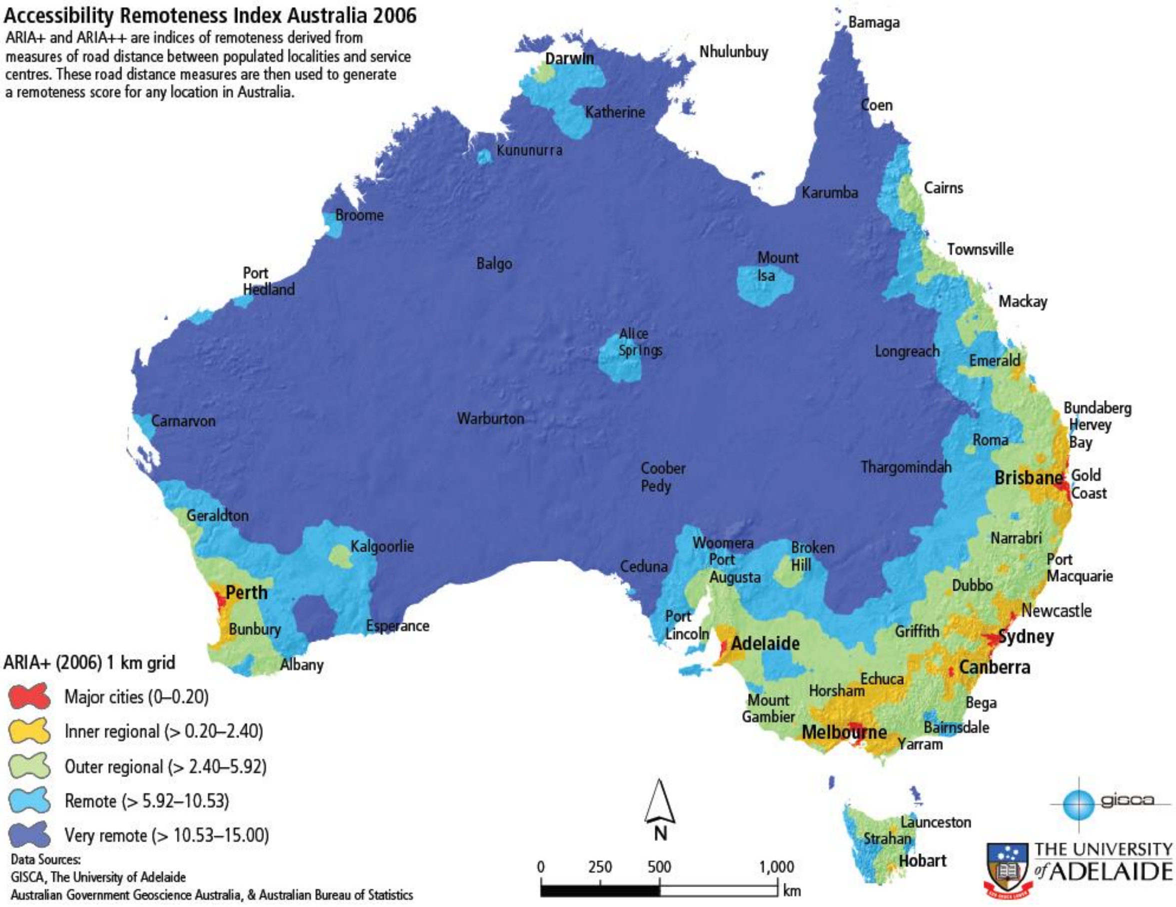


Figure 1.4 Distribution of road infrastructure (Jennifer Baxter March 2011)

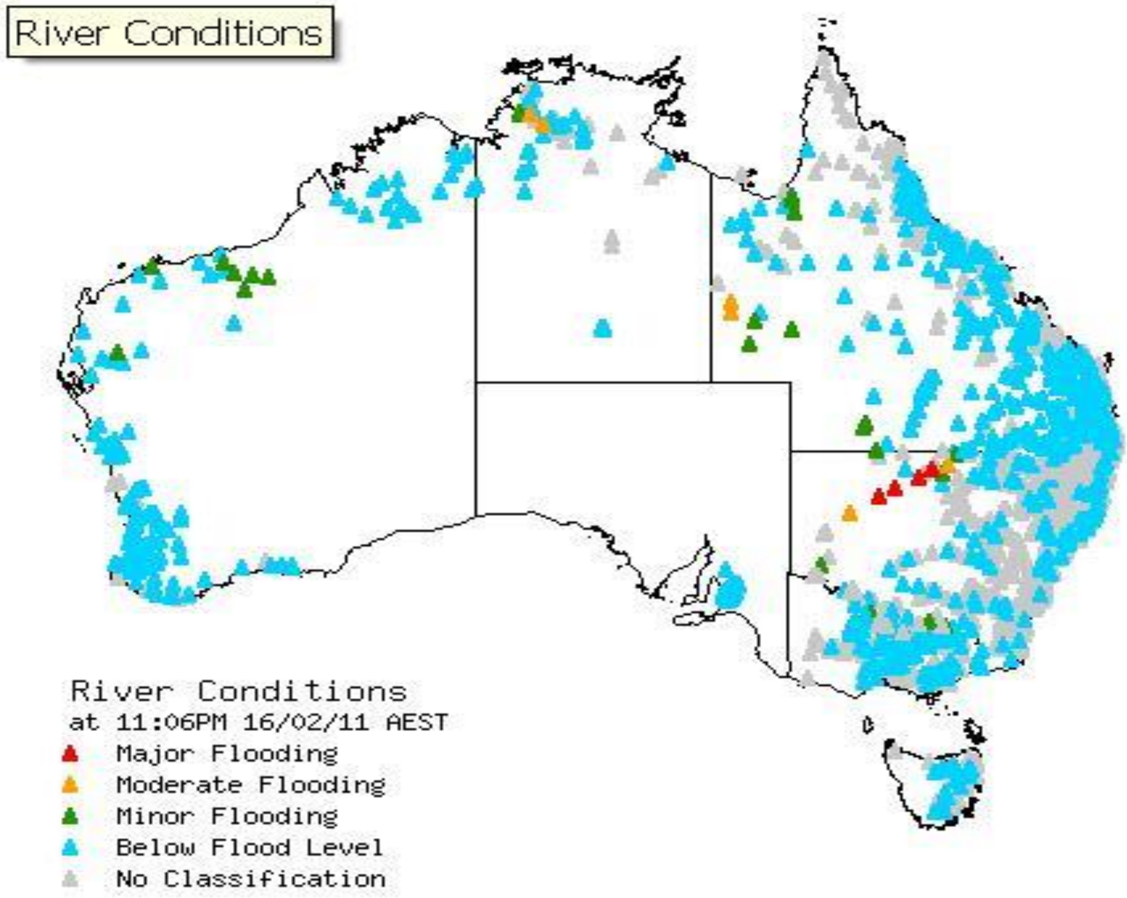


Figure 1.5 Flood events distribution(Australia Government Bureau of Meteorology 2011)

In the past few years, population increases have brought more residents, mainly of the younger generation, to coastal areas than anywhere else. The growing population would lead to a more vulnerable population that will suffer flood events. The increased demands on transportation in the coastal region produce more intensive road network around coastal zones (Hugo 2003). The increasing density of road networks would increase the number of bridges that are exposed to the extreme storm and flood events (Bankoff, Frerks & Hilhorst 2004). Also, the costs of recovering bridges that are damaged in flood events would be higher due to higher labour costs, the application of new technology, a larger building scale, the need for more overpasses and associated facilities, etc. All these reasons above will lead to a higher post-disaster recovery cost.

Mitigation disaster relocation has been discussed, studied and observed for several years. It is believed to be the most effective disaster mitigation method to keep local communities away permanently from high-frequency, predictable severe natural disasters permanently and reduce long-term rehabilitation costs after flood events (Perry & Lindell 1997). It is applied by different counties after different types of natural disasters as well as in disaster prone areas. Some local councils have been trying to relocate some of the communities residing in disaster-prone areas. For example, Darwin move out residents for disaster mitigation purpose in 1979 (Perry & Lindell 1997). The Federal Emergency Management Agency even has a disaster mitigation relocaiton programs serves residents in disaster vulnerable reigon in the united states. In Japan, there is an Act on Special Financial Support for Promoting Group Relocation for Disaster Mitigation. However, relocation and evacuation the local community in disaster-prone area is not often conducted vary successfully. There are two reasons: On the one hand, the local government can only afford to relocate a limited number due to the massive costs. On the other hand, the local community will not want to leave their homes. In the 1979, the local government force residents in Darwin relocated their homes. But currently, relocation always respect personal willingness. The government measures become provide help for relocation(Matthews et al. 2002). In Lockyer Valley, the majority of the residents insisted that they would not leave their homes after three flood events in 2010, 2011 and 2013. In these circumstances, the majority of the population would not move out from the flood vulnerable region. The local council has to maintain the access to bridge and other road infrastructures in the flood vulnerable region. Currently, there is no strategy shows that the government would move out a large number of residents in disaster vulnerable areas in Australia, although Bushfire researchers in CRC have found that it is cheaper to move people out of high risk areas than rebuild their houses (Clint Jasper 2015). Relocation become inexecutable strategy even if it works in high disaster risk areas.

In conclusion, two trends in the near future should be mentioned: First, the high-frequency of extreme weather and climate change will bring more floods to Australia. Second, The increasing population around flood vulnerable region will increase the demand on bridges and other road infrastructures. Without effectively relocating the majority of the population, two trends will lead to more risks that bridges will be exposed to flood events: (1) Bridge would suffer more damage in the future. (2) More residents will experience traffic problems due to bridge damage. In conclusion, there will be more losses due to bridge damage in the future.

1.3 The impacts of road infrastructure destruction on the local community in natural disaster

The Cooperative Research Centre (CRC) summarized the economic impacts to explore the economic losses that are caused by infrastructure damage (Jane Mullett 2015). According to the CRC, the possible effects on the local community can be calculated and separated into four aspects (Figure 1.6). Most of the natural disaster research papers admitted that the economic impact of natural disasters can be distinguished as direct tangible, direct intangible, indirect tangible and indirect intangible economic implications (Hallegatte & Przyluski 2010; McKenzie, Prasad & Kaloumaira 2005).

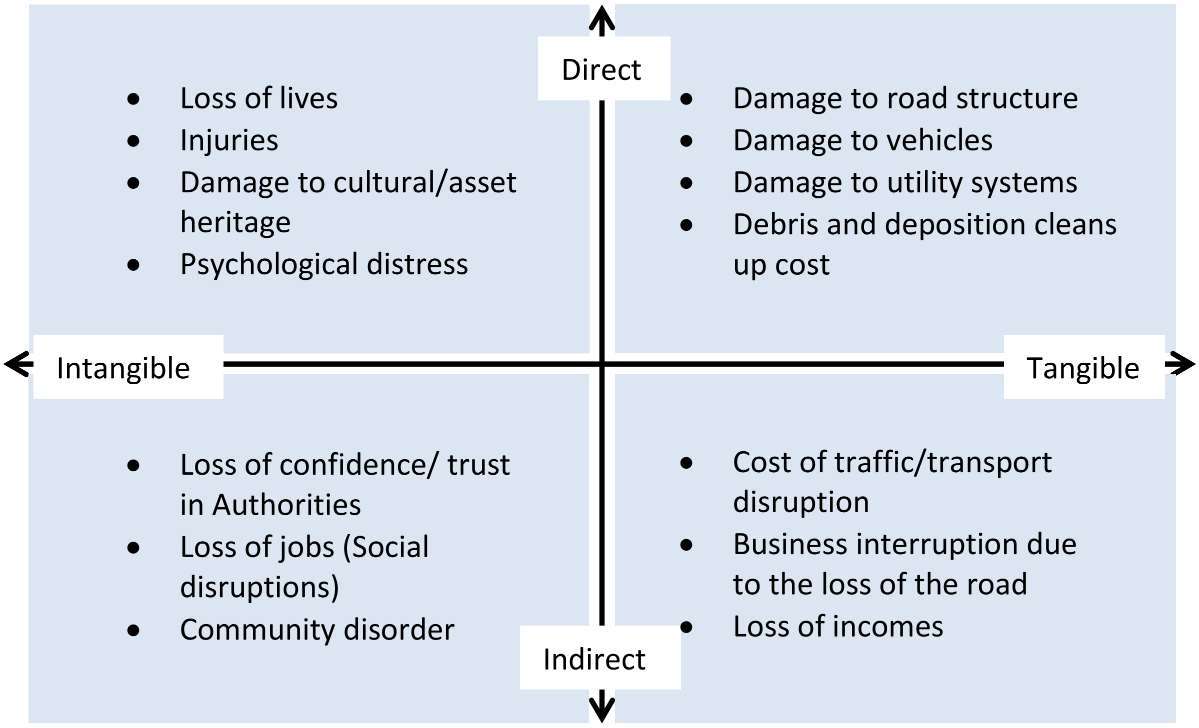


Figure 1.6 The losses caused by road infrastructure destruction(Jane Mullett 2015)

The economic impacts which are caused by the road infrastructure damage have broad effects on different aspects of the local community. Some of the natural disaster impacts will even create profound second effects on the long-term development and economy. These impacts should be identified and verified. The more specific the category is, the easier to calculate the economic losses after natural hazards (McKenzie, Prasad & Kaloumaira 2005). By reviewing previous research and interviewing the victims of the road infrastructure disruption, different impacts are summarized into the matrix (Figure 1.6). Category economics by various characters can avoid double accounting the economic effects of natural disasters (Gentle, Kierce & Nitz 2001).

As a part of the CRC research, this research will focus on the economic impacts that are created by bridge damage in flood events. As an important part of road infrastructure, the bridge will have similar economic impacts on the local community. The economic impacts should be identified and summarized.

1.4 Bridge damage in flood events

Bridges play a significant role in a road network, and they are designed to resist flood events, based on the design and construction practices available at the time of construction planning. When a bridge is damaged in flood events, the road networks that are located on the two sides of the river are disconnected, which cause short- and long-term inconvenience and obstacles to social connection, business interaction, and community activity. These adverse effects create negative economic impacts, and the correlative economic losses will accumulate until the bridges get recovered (Negi et al. 2013).

Often, After a flood, there are two forms of damage, which can affect the bridge functioning and disrupt traffic:

(1) Debris: the accumulation of debris on the bridge interrupts traffic. In some cases, the bridge structures have not been destroyed in flood events. In fact, the reliability and stability

of the bridge are adequate for transporting vehicles. However, the transportation flow is interrupted due to the debris built up on the bridge.

(2) Damaged Structural elements: the structural elements of the bridge are destroyed during the flood. Therefore, the stability and reliability of the bridge cannot be guaranteed. The structure elements of the bridge should be inspected first after a flood event. After inspection, repaired/replacement activities need to commence for the damaged bridge structures.

In flood events, a bridge's condition can be as good as before disasters, or a bridge can be completely destroyed. In both situations, access to and the function of a bridge could be impacted because of debris accumulation and physical damage to the bridge body. The function of a bridge would change in three stages when bridge suffered a flood event (Figure 1.7):

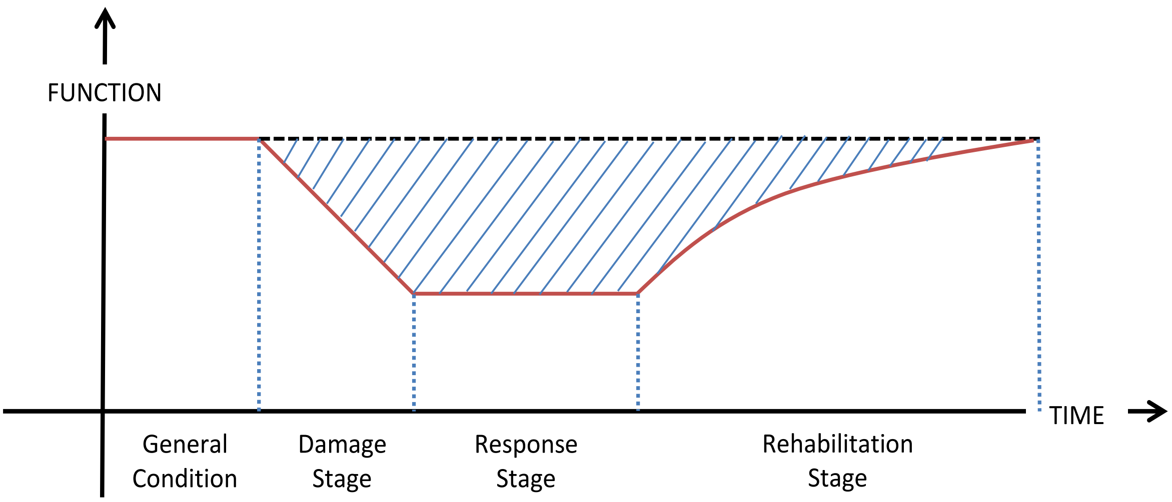


Figure 1.7 The bridge function change during and after flood events

The first stage includes the damage that happens to a bridge during a flood event. The duration could range from a few hours to several days (flood events can last for several days or even more than a month). In this stage, the function of the road decreases until the end of the flood event (Przyluski & Hallegatte 2011). Bridge damage and debris accumulation occur during this stage. This stage determines the availability and accessibility of a bridge after flood events.

The second stage can be described as the response stage. During the stage of response, the damaged bridge could be closed out of safety concerns while waiting for inspection and repair activities. There are three features at this stage: First of all, the function of the bridge will stay in the condition it was in during the first stage. Secondly, there is no more direct damage to the bridge. The main economic losses during this stage are indirect losses due to bridge access and bridge availability. Thirdly, the local government and community begin to prepare rehabilitation at the response stage. Rehabilitation would include inspection and recovery work. When the bridge is closed or can only partly open to the public, the local council would take action to relieve adverse effects such as post-disaster traffic guide. The reaction speed after a natural hazard depends on the preparation before the disaster, including plans, facilities, and materials (Fiedrich, Gehbauer & Rickers 2000). If the local council organised adequate preparation, the time that is spent on the response will decrease.

The third stage is the recovery stage. In this phase, the function of the road will gradually increase until it is fully recovered from its damage. There are two conditions after bridge recovery: (1) The damaged bridge will recover to the pre-disaster conditions, or reach a reasonable condition that can support local transportation. (2) After repair, the bridge would be better than the pre-disaster condition. Reasons for this circumstance are applying new technology, new designing, etc. (Rogers 2011). When the function of damaged bridge reaches the level before disasters, negative effects is considered eliminated. In most of the research, it will be assumed that all damages will be repaired as the condition before catastrophen (Gentle, Kierce & Nitz 2001; Meyer et al. 2013). The duration of the recovery is one of the most important variables with the potential to influence the social activity, collective activity, and productive activity on both sides of the river. The longer the duration of recovery, the more the indirect losses will be (Przyluski & Hallegatte 2011).

1.5 Measure the economic impacts after flood events and the rationale of estimating economic impacts of the bridge destruction

1.5.1 Measuring the economic impacts

Bridge disruption related losses are measured in two ways. For the direct/indirect tangible economic effects, these economic impacts can be measured by monetary methods. However, the direct/indirect intangible losses are hard to measure by monetary flow (Hallegatte & Przyluski 2010), such as the trust loss of the local government and the value of the historic bridges. According to the interview by the CRC, some of the residents lost their trust and confidence in the decision-making of the local council (Jane Mullett 2015). These types of intangible losses also need to be measured or properly interpreted.

After flood events, the local council and the local community would like to know the economic impacts that were caused by the disruption of the bridge. Three aspects can be concerned after flood events: First of all, the expenditure on the bridge recovery, which is one of the direct tangible costs, needs to be estimated (Cho et al. 2001). Secondly, the indirect tangible losses, which are mainly caused by the lack of access due to bridge damage, need to be estimated. Impacts can be inconvenient traveling for bridge users and local businesses (Hopkins, Lumsden & Norton 1993). This kind of loss will affect the regional economy performance in the near future.

Thirdly, the local council would consider some intangible economic impacts that would impact its governance and status in the local community. The loss of the authorities of the local council, the psychological problem caused by a bridge disruption and the disorder of the labour market/local community are three main intangible issues which the local council should take into consideration.

1.5.2 The importance of estimating economic impacts of bridge damage

An accurate assessment report after a flood event can be a valuable reference to support the estimation of the required rehabilitation activities. It can help the local council to identify the vulnerable regions and victims after flood events. Therefore, the local council could draw up a precisely targeted solution to help them to relieve their losses. The most affected residents and industry could get out of their difficult positions with more support from the local council. Otherwise, the assessment will point out the weakness in the road infrastructure system. First of all, the easily damaged structure component could be identified and improved. The local council can enhance the weak part by improving the flood resistance of the bridge, relocating the road infrastructure, and providing more alternative ways (Croope & McNeil 2011). In one word, an accurate assessment report is crucial to the local council to make pre-disaster preparation. Secondly, the local council can make strategy recovery of the most affected traffic. The carrying capacity of alternative road and surrounding road system can be verified after flood events. After bridge damage, the traveling will more rely on alternative road network (McDaniels et al. 2007). That will lead to increasing travel time and traffic congestion in the alternative road (Cho et al. 2001). It is critical to test whether these alternative paths can meet the demand of traveling. Evaluating traffic demand and carrying capacity could be evidence for the local council to support post-disaster traveling.

1.6 Research questions and objectives

1.6.1 Research questions

There are 2 main research questions in this thesis:

1. What are the economic impacts of bridge damage in flood events? How to categorize these economic impacts systematically?

Researchers have attempted to apply methods or models to measure the economic losses after natural disasters. The first step is to define impacts accurately. In different studies, different research purposes and scopes would lead to different category scopes. The economic impacts had been included in various categories by different papers (Hughes 2003).

In this study, the correlation between bridges and different economic sectors would be identified. Apparently, road infrastructure is the foundation for other infrastructure facilities and has an impact on other economic sectors. As an important part of road infrastructure, a bridge collapse affects the surrounding road networks and cause significant economic losses in other social sectors. This research would apply proper scope to categorize different types of economic impacts that are caused by bridge damage. There is no specific research identifying the economic impacts of bridge destruction in natural disasters. Therefore, economic impacts need to be identified and summarized from previous research and interviews.

2. How can thees economic losses be measured?

After categorizing the economic impacts of bridge damage from a flood event, proper methods and models should be applied to estimate the economic impact of each type of loss. There are different approaches that attempt to quantify the economic losses due to severe flood events. However, most of the models have not been sufficiently validated (Merz et al. 2010). In addition, few models can be applied to the local community because they focus on the gross economic level. This research will concentrate on identifying effective and efficient ways to help the local community to measure the economic impacts at a regional level including the direct cost of the repair/replacement of the concrete bridge after a flood event, the indirect costs for the residents, etc. Some economic losses, such as direct and indirect intangible losses, which are hardly be measured in monetary terms, need a proper method of interpreting their impact level.

1.6.2 Research objectives

The economic impacts of bridge damage due to flood events on the local community have not been discussed and analysed systematically. Therefore, this research will focus on four aspects:

(1) Identifying the economic impacts of bridge damage in flood events on the local council/community
(2) Categorizing the economic impacts systematically, dividing them into direct and indirect and tangible and intangible
(3) Introducing proper models to measure the tangible losses and interpret the intangible losses accurately
(4) Demonstrating the integrating model in case study

1.6.3 Research significance

Road networks are the most important lifeline system because they support the construction and maintenance/repair of the other lifeline system (Hopkins, Lumsden & Norton 1993). Developed economies rely on the transportation system heavily (Dalziell & Nicholson 2001). There will be severe consequences when roads are destroyed in flood events. As a significant part of the road infrastructure, bridges have not only a high construction cost but also an enormous output value, which could impact surrounding transportation systems (Xie & Levinson 2011). Bridge collapse/damage will cut off or increase the difficulty of connection and accessibility on both sides of the river including social, collective and business activities. Therefore, bridges could produce impacts on stakeholders that rely on traveling across the bridge. On this circumstance, it is a better way for the local community to estimate their potential costs and output value that happen during bridge recovery.

The local community needs an approachable method to help them to assess the economic impacts on the local economy and local community. The local council should have comprehensive information about economic impacts of bridge damage during rehabilitation. This kind of estimation would offer advantages to local communities:

(1) Estimation can point out which area would be more vulnerable and suffer the most loss during bridge recovery.

(2) The targeted strategy could be made to support most vulnerable areas to overcome traffic and transportation problems.

(3) Estimation could help the local community to plan and verify before/post disaster preparation, disaster mitigation solutions, and reconstruction process to relieve damage in different areas.

(4) Estimation could be evidence to plan recovery and improve recovery efficiency.

1.7 Outline of the thesis

This thesis has seven main chapters. Each chapter would include one theme that would relate to research topics:

Chapter 1 introduces reasons for the direction of this investigation. This chapter explains the significance of this investigation. That includes the importance of bridges, threats of damages from natural hazards, and future challenges from flood events. It also states research topics and questions.

Chapter 2 summarizes the current state of knowledge on economic impacts of bridge damage in flood events. Also, it discusses present concepts and models that are relevant to the measurement of economic impacts.

Chapter 3 describes the research methodology in detail including the research plan, data collection methods, research instrument, type of data to be collected, and data analysis.

Chapter 4 summarizes the economic impacts of bridge damage in flood events from previous investigations. This chapter discusses any economic impacts that could be caused by bridge damage in flood events. It also groups different types of economic impacts by a causes and effects analysis.

Chapter 5 uses current concepts and models to address and measure economic impacts that are identified in Chapter 4. The concepts includes performance groups and damage states. Models would mainly focus on detouring costs of bridge users and business interruption.

Chapter 6 uses the Kapernicks Bridge, which is located in Lockyer Valley region, Queensland, to illustrate the integrating model. It will also discuss current limits to apply the integrated models.

Chapter 7 offers conclusions regarding research objectives, contributions to current knowledge, implications to investigations and recommendations for further research.

CHAPTER2 LITERATURE REVIEW

2.1 Natural disasters and disaster impact

Natural disasters are described as geophysical, atmospheric, or hydrological events (Twigg 2007) or as a major adverse event resulting from natural processes of the Earth (Izquierdo 2015), for example, earthquakes, windstorms, tsunamis, flood events, heat waves, and drought. Typical disasters in Australia are mainly severe storms, drought, floods, earthquakes, bush fires, heatwaves, and landslides (Gentle, Kierce & Nitz 2001). These disasters can lead to property damage or even loss of lives, and typically have some economic impact on the community (Bankoff, Frerks & Hilhorst 2004). Natural hazards threaten all the countries around the world. The reality is that available and effective measures are not available to predict and prevent future disasters due to their unexpected forms, magnitudes and location(Zhou, Wan & Jia 2010). The economic losses that is caused by natural disasters could be tremendous. A study that is taken by FAO (Food and agriculture organisation of the United Nation) summarized that natrual disasters cause more than 1.1 million deaths and up to 1.5 trillion $ in damage between 2003 and 2013 (Food and Agriculture Organization of the United Nations 2015). Besides, there are also large amount of investment on improvement of infrastructure to as mitigation of natural disasters. Disaster reports also pointed out that future natural disasters would be more costly. As populations and economies continue to grow, larger numbers of people and more infrastructure are likely to be located in hazard-prone areas (Vorhies 2012).

As a disaster-vulnerable country, almost the whole territory of Australia is affected by different types of natural disasters. According to the statistics collected by the United Nations Office for Disaster Risk Reduction (UNISDR), 162 natural disasters occurred and 959 citizens were killed in these hazards which were recorded from 1980 to 2010 in Australia, and the economic losses were the equivalent of approximately equals US$ 926,451,000 per year (UNISDR 2013). The Statistics present costs on post-disaster recovery in the following areas (Benson & Clay 2003; McKenzie, Prasad & Kaloumaira 2005):

(1) Social sectors, such as housing, education, and health;

(2) Infrastructure sectors, such as transportation, power, and water supply;

(3) Economic sectors, such as agriculture, business, industry, and tourism.

Statistics is one type of method for estimating losses in natural hazards. It calculates costs and expenditures on physical property and assets recovery directly. However, it often ignores the intangible correlations between different social sectors. For example, infrastructures can impact economic sectors. In natural hazards, the physical damages are only one small part of economic losses. There will be severe secondary effects which are indirectly caused by natural disasters (LITAN 1999). In addition to the expenditures that are spent on repair/replacement of the damaged physical assets, interruption of different production process due to physical damages is worth being clarified and discussed. The economic impacts of natural disasters should consider the large amount of indirect losses of total potential outputs after natural hazards. In this research, calculating expenditures on recovering a damaged bridge is one part of the research purposes, while the indirect losses and impacts that bridge users and stakeholders would suffer from after bridge damage are the main concerns.

Financial analysis and economic analysis

Two different types of analysis have been conducted after flood events by previous researchers:

(1) Financial analysis (Merz et al. 2010) concerns itself more with the costs to the individual or the entity that is directly affected by the disasters. This is the method insurance and finance companies would use to calculate financial losses after flood events.

(2) Economic analysis would analyse direct and secondary benefits, and costs flow as a result of bridge damage (Gentle, Kierce & Nitz 2001; McKenzie, Prasad & Kaloumaira 2005). This analysis is widely used by the decision makers (Handmer, Reed & Percovich 2002). Compared with financial analysis, the economic analysis is more complex. Economic analysis would explore relations between different social sectors. Economic analysis will identify and calculate how one damaged economic sector would lead to losses in other areas. Apparently, some impacts can be measured by the monetary flow. However, others impacts, for example, loss of lives, loss trust in the government, etc., have no market value (McKenzie, Prasad & Kaloumaira 2005). There are two different types of economic impacts, tangible and intangible, that is, impacts with market value and without market value.

Currently, most of the studies focus on the economic analysis instead of financial analysis of natrual hazards. They explore the impacts and economic correlations between different social sectors. In this research, an economic analysis of a damaged bridge is conducted to clarify its economic impacts on other social sectors in a flood event. After the identification of economic impacts, all economic impacts need to be properly classified. So a clear classification method is required.

2.1.1 Classification of the economic impacts

Most of the current economic studies use similar classification methods. These studies would adjust definitions and scopes of each type of impact due to their research objectives and scopes. Two mainstream classification methods are discussed and compared in this research:

(1) The mainstream category methods distinguish different types of losses by the direct (immediate) and indirect (secondary) effects. Direct impacts are damages that are caused by the disasters themselves. The indirect impacts are the ripple effects or consequences, which are the secondary effects, and not caused by the disaster events themselves (Bubeck & Kreibich 2011a; Hallegatte & Przyluski 2010; McKenzie, Prasad & Kaloumaira 2005; Merz et al. 2010; Smith & Ward 1998). In this research, direct impacts and indirect impacts are

different due to different research purposes and scopes. For example, the business interruption is separated into direct, indirect or a separate category by different researchers due to their research scopes and objectives (Hallegatte & Przyluski 2010).

In addition to direct and indirect impacts, research also introduces tangible and intangible to distinguish different economic losses by whether they can be measured by monetary flow or not (Merz et al. 2010). Tangible cost can be interpreted as objects with a market value or resource flows that can be easily specified in monetary terms - for example, the damaged assets- while intangible cost always has non-market value or difficult to give a monetary value, such as the loss of lives (Smith & Ward 1998).

(2) In some specific research, the economic impacts are classified by different cost assessment methods. In Costs of Natural Hazards Research (CONHAZ) (Bubeck & Kreibich 2011b; Meyer et al. 2013; Przyluski & Hallegatte 2011), the classification of economic impacts is categorized into five types: 1. Direct costs 2. Business interruption 3. Indirect costs 4. Intangible costs 5. Risks mitigation costs.

The second classification method that is used by CONHAZ is not suitable for this research. There are two concepts that are difficult to apply to this research. The first one is the business interruption. In some studies estimating the business disruption, that is caused by flood events, the flood creates direct damage on the property of business. Otherwise, properties that are also damaged in flood events could also create business disruption - for example, power, water, the internet, and transportation. Therefore, business disruption cannot be simply separated into direct or indirect. However, in this research, business disruption is an indirect loss due to transportation problems that are caused by bridge damage. Secondly, mitigation costs are difficult to define in this research. For example, a steel bracing project after flood event can be treated as preparation and mitigation costs for the next flood events. However, it is one part of direct repair costs after a flood event.

In conclusion, the first classification is more suitable for this research. That means economic impacts would be categorized into four aspects: (1) Direct impacts (2) Secondary impacts (3) Market value (4) No market value

2.1.2 Economic impacts of road infrastructure disruption in natural disasters

After a flood event, different consequences will appear in various sectors of society. Research mainly focuses on analysing economic impacts on six social sectors (Bubeck & Kreibich 2011a): 1. Private households, 2. Industy and manufacturing, 3. The services sector, 4. The public sector, 5. Lifelines and infrastructure, 6. Agriculture. Some studies also throw light on evacuation, disaster mitigation, post-disaster recovery, and disaster management. Most of the present studies pick up one or two aspects to explore economic effects (Merz et al. 2010). In these studies, the same research topic would also have different economic impacts, for two-reasons: On one hand, economic impacts are decided and limited by knowledge and personal experience of researchers. On the other hand, economic impact components also vary a lot due to different research purposes and scopes (Hallegatte & Przyluski 2010). Therefore, cooperation and coordination would be important to having a full, better understanding of this area.

The Cooperative Research Centre (Setunge et al. 2015) in Australia conducted a cooperative research on understanding community resilience to road network disruption. Before CRC, there were already efforts in this area. In their 1993 research, Hopkins, Lumsden, & Norton pointed out that road infrastructure is the most critical system in these sectors because it connects and supports the running of other areas and even of society (Hopkins, Lumsden & Norton 1993). The majority of studies focus on network reliability, performance, and recovery of the road network after a natural disaster (Chang, SE & Nojima 2001; Karlaftis, Kepaptsoglou & Lambropoulos 2007; Sakakibara, Kajitani & Okada 2004; Sumalee & Kurauchi 2006). The others applied studies on exploring economic impacts or performance of road infrastructure in natural hazards (Cho et al. 2001; Xie & Levinson 2011). To sum up, the understanding of road infrastructure and its important role in the local community in a natural disaster is still limited.

Research of CRC focuses on road infrastructure damage in four main types of natural hazards in Australia, which are flood, earthquake, bushfire, and climate change. Their first stage work has already reviewed previous studies and interviewed victims in disaster-affected regions. A matrix has already been developed to summarize economic impacts of road infrastructure disruption in natural disasters (figure 2.1) (Jane Mullett 2015; Setunge et al. 2015).

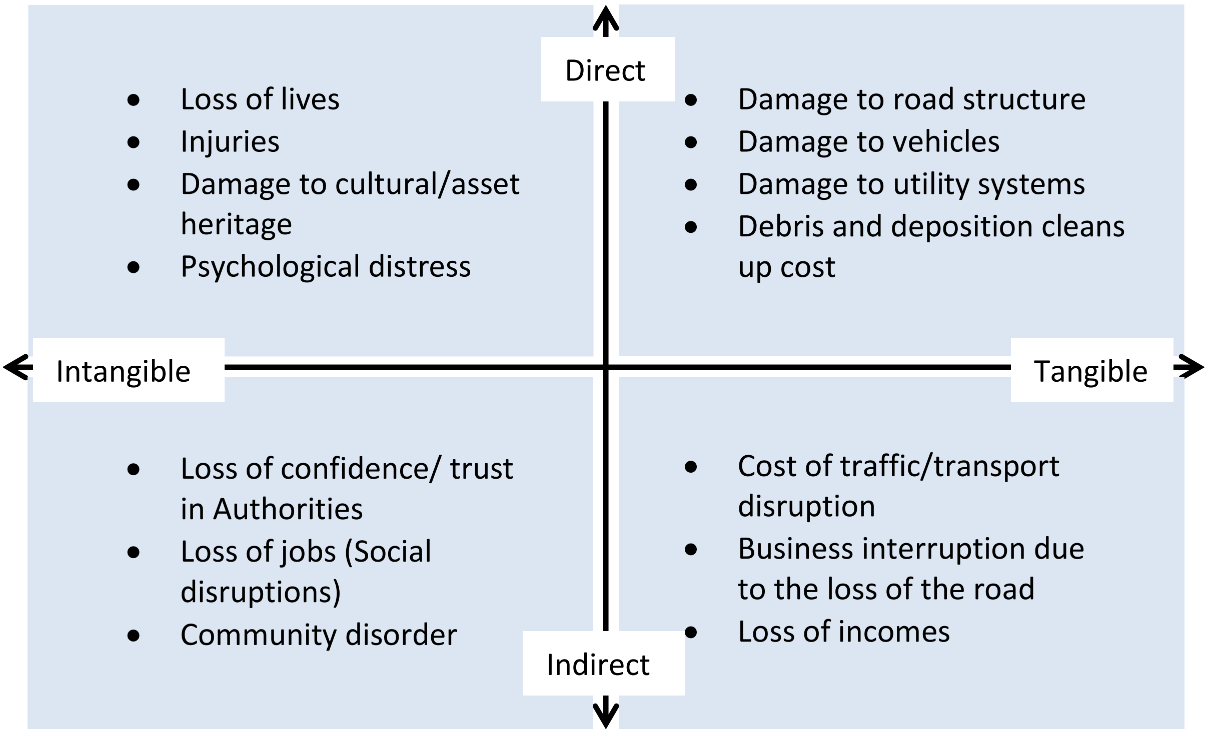


Figure 2.1 Economic impacts of road infrastructure damage

2.1.3 Significance of bridges in road infrastructure

As a significant part of road infrastructure, bridges have a special status in road infrastructure. It always connects two separate transportation systems on the two sides of the river or road networks. Despite impacts on other social sectors, the bridge will affect the performance of the surrounding road networks (Dalziell & Nicholson 2001). In some extreme cases, the bridge is the most important connection with the outside world. The Vanuatu earthquake in 2002 led to the collapse of a bridge. As a consequence, the local government had to use boats and helicopters to transport food and shelter to the local community (McKenzie, Prasad & Kaloumaira 2005).

The special value of a bridge can be illustrated in two aspects: (1) A bridge has a large construction value. To repair or rebuild a damaged bridge needs a significant amount of money. As the Lockyer Valley report said, "Following the devastating flood event of January 2011, 40 of the Lockyer Valley's 48 bridges required some form of repair works, with preliminary repair and replacements costs of all 40 bridges totalling $11 million (Queensland Reconstruction Authority 2015). (2) A bridge can have a significant economic output value to the local economy and "should not be closed without large consequences for users" (Hallegatte & Przyluski 2010). In his 2012 research, Petrucci marked on the bridge collapse situation as the most severe damage on the regional community (Petrucci 2012). On one hand, a bridge closure can produce a significant amount of indirect loss (Seifert et al. 2010). On the other hand, bridge is one of the most valuable infrastructure assets which are necessary for quick economy recovery (Kreimer, Arnold & Carlin 2003).

In conclusion, a bridge can create great economic impact and can indirectly affect other sectors by impacting surrounding road networks. To clearly identify the economic impacts of bridge damage, there needs to be a precise analysis of causes and effects due to bridge damage.

2.2 Bridge damages and access

During flood events, two conditions could impact function and accessibility of the bridge: (1) Natural disasters could damage the physical body of the bridge. Physical damage can decrease strength and carry capacity of the bridge. (2) Bridge accessibility could be impacted by debris that is created by natural disasters. It is a common situation that debris, which is carried by flood events, could build up on the bridge surface and the upstream side. Debris and debris cleaning could block normal traffic.

Both debris quantities and the post-disaster condition of the bridge would be important factors in evaluating the post-disaster accessibility of the bridge. Debris quantities would impact cleaning method and clean time. The bridge damage condition is relevant to safety, availability, repair time (close time), and accessibility of a bridge after flood events.

In this part, cleaning debris around the bridge and evaluating bridge damage conditions would be important to measuring availability and accessibility after flood events. A debris clearance guide and a bridge damage state method are needed.

2.2.1 Debris and debris clearance after flood events

The debris which is defined as the waste created by disasters (Çelik, Ergun & Keskinocak 2015), will affect the accessibility of the road infrastructure. As Kreibich claimed in his 2009 research, debris flow creates lots of bridge closure and needs more attention (Kreibich, H et al. 2009). Cleaning will take a significant part of the disaster rehabilitation costs. In some case, debris cleaning can even account for 27 percentage of the total loss (FEMA 2007). Regarding the accessibility of road infrastructure, debris and debris removal can lead to traffic congestion or even road closure. To minimize the negative effects caused by the debris, different methods, for example, the POMDP model, a decision support method to help debris cleaning and disposal (Fetter & Falasca 2011), are developed to help the local government to optimize the efficiency of debris cleaning. At present, many of the studies focus on handling debris and cleaning debris quickly. Few studies make contributions on estimating debris quantities that are created in a specific catastrophe, such as a large amount of debris which is generated by the Haiti earthquake (Booth 2010). However, estimating debris quantity still relies on survey and observation. There is still a knowledge gap in using parameters to predict or quantify the debris generated in specific regions during a flood event. It has been decided that estimation of debris quantities depends mainly on observation and survey.

Compare to estimate all flood-impacted areas, estimating the debris quantity around the damaged bridge is easier because (1) the area that needs to be estimated is smaller and (2) the debris constitution around the damaged bridge is simpler. Fewer samples need to be taken, around the damaged bridge, to estimate debris constitution and quantity.

In terms of debris cleaning, the cleaning progress includes debris collection and debris disposal (FEMA 2007). The collection progress can also be separated into two steps: collection and transportation (Ghose, Dikshit & Sharma 2006). Debris collection involves costs of collecting debris in the disaster-affected region and transporting debris to well-designed dump sites.

There is a government guide for waste disposal in Australia. Debris should be properly treated to minimize its impact on surrounding environment. Debris can be separated into different types of waste: general waste and green waste. The other subcategories include debris that is dry or wet, solid or not, etc. Some of the debris can be recycled, and other types of waste can be burned or buried. The most widely used waste disposal methods in Australia are recycling and landfill. The costs for different types of waste are varied in different conditions and different states (Table 2.1) (Productivity Commission 2006).

Table 2.1 Average landfill costs

Region	Best Control (AUD)			Poor Control (AUD)		
	Dry	Wet (temperate)	Wet (Tropical)	Dry	Wet (temperate)	Wet (Tropical)
Small urban	101.7	101.5	101.4	93.6	96.6	97.7
Medium urban	61.7	61.5	61.4	64.1	67.1	68.4
Large urban	41.7	41.5	41.4	49.3	52.3	53.7
Small rural	100.8	100.6	100.5	88.1	91.1	92.4
Medium rural	60.8	60.6	60.5	58.6	61.6	62.9
Large rural	40.8	40.6	40.5	43.9	46.9	48.2

There are also wastes that are created during bridge repair. In Australia, the government recommends that the construction companies recycle construction wastes. Some of the construction wastes are disposed of with debris; others are delivered to recycling sites. Recycling has two advantages: (1) it does not waste area and pollute the surrounding environment. (2) Recycled materials would save environment material and resources. In different states of Australia, waste recycling will charge gate fees. In this research, debris would include both debris and construction wastes. The costs for debris clearance would include debris collection, transportation, and disposal.

2.2.2 Bridge structural damage after floods

Despite the debris, the direct damage on a bridge body during a flood event would directly impact the bridge strength and traffic safety. A proper damage state method should be useful to describe the bridge safety and availability. Damage states also important to predict repair methods, repair costs, and the time limit of the repair project.

After flood events, there are different kinds of damage rating methods which are currently used to describe different levels of road infrastructure damage. Three widely used damage state methods are introduced to various purposes and areas in Australia:

(1) The Department of Main Roads in Queensland and Melbourne Council in Victoria use a similar damage grade method to describe the road condition in periodicity inspection (figure 2.4) (Queensland. Dept. of Main Roads. Road & Engineering 2000). Five levels are used to describe the health condition of the road infrastructure, especially bridges. This condition state rating system is developed to ensure the road infrastructure has the adequate stability and reliability to support the transportation. This damage rating method can only be used for estimating safety of the whole structure. The small number stands for a good condition, while the large number marks the road infrastructure as dangerous. It has two levels to illustrate that the road infrastructures are in a good condition: When the bridges have a score that equals to or exceeds level three, bridges will need some more detailed inspection, taken on by professional companies. These detailed inspections will identify the damaged structure components. The next step is to repair/replacement of damaged bridge structures and make the bridge reach a reliable condition; a score less than three means that the bridge does not need repairs or only some routine maintenance.

Table 2.2 Damage Grade of QLD Road Inspection

Condition state	Subjective rating	Description
1	Good	Free of defects
2	Fair	Free of defects affecting structure performance, integrity and durability
3	Poor	Defects affecting the durability which require monitoring, detailed structural engineering inspection or maintenance
4	Very poor	Defects affecting the performance and structural integrity of the structure which require urgent action as determined by a detailed structural engineering inspection
5	Unsafe	Bridge must be closed

(2) Both CONHAZ and Maiwald and Schwarz (2010) use a similar five-grade method to distinguish different levels of damages of physical assets after disasters (Bubeck & Kreibich 2011a; Merz et al. 2010). Houses and road infrastructure are two main part in this method (Figure 2.2). This grade damage method is also based on the damage observation and engineers' judgement and five grades to summarize building damage condition after disasters. The advantage of this method is that it would consider the surrounding areas as an important aspect in measuring economic impact. The debris pollution would be taken into consideration. For bridge recovery, debris clearance is an inescapable part.

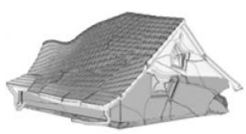
D_i	Damage		Description	Drawing	Example
	Structural	Non-structural			
D1	no	slight	only penetration and pollution		
D2	no to slight	moderate	slight cracks in supporting elements impressed doors and windows contamination replacement of extension elements		
D3	moderate	heavy	major cracks and / or deformations in supporting walls and slabs settlements replacement of non supporting elements		
D4	heavy	very heavy	structural collapse of supporting walls, slabs replacement of supporting elements		
D5	very heavy	very heavy	collapse of the building or of major parts of the building demolition of building required		

Figure 2.2 Damage states that are used by CONHAZ (Merz et al. 2010)

Besides, this method also consider water resistence of different construction material. The flood resistance of different materials is shown in figure 2.3(Figure 2.3) (Schwarz & Maiwald 2008). It can group different performances of road infrastructure with different construction material in flood events. In this method, building design and materials could be critical parameters to describe building damage more accurately and predict building damage in similar flood conditions. By summarizing different performances of different construction materials, the ratio can be calculated to predict bridge damage states after flood events. There is the vulnerable range of buildings with different building materials (Table 2.3).

Table 2.3 Flood Vulnerability Class

Classification of building type	Short	Flood vulnerability class (High to low)				
		A	B	C	D	E
Clay	Clay					
Prefabricated	PF					
Framework	FW			c		
Masonry	MW					
Reinforced Concreted	RC					
Flood resistance designated Buildings	FRD					
	Most likely vulnerability class					
	Probable range					
	Range of less probable, exceptional cases					

This damage state method illustates that different designingd and construction material of bridge should be considered separatedly in one flood event. To evaluate average damage condition and summarize trait points of damaged bridges, it is better to group bridge with same designing and building materials.

(3) HAZUS has applied a specific damage state method to describe bridge damage after disaster events. This approach, which also applies five different levels to describe the different damage levels, has been used by the Federal Emergency Management Agency (FEMA) to measure the repair/replacement cost (Merz et al. 2010).

Table 2.4 Damage states by HAZUS

Damage state	Description
No damage	No damage
Slight	Minor cracking and spalling to the abutment, cracks in shear keys at abutments, minor spalling and cracks at hinges, minor spalling at the column (damage requires no more than cosmetic repair), minor cracking to the deck, or slight damage to operator house.
Moderate	Any column experiencing moderate (shear cracks) cracking and spalling (column structurally still sound). Moderate movement of the abutment (<2 in.), extensive cracking and spalling of shear keys. Any connection having cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure, moderate settlement of the approach, moderate scouring of the abutment or approach, damage to guardrails, the wind and/or water damage to operator house resulting in switchboard or content damage.
Extensive	Any column degrading without collapse—shear failure (column structurally unsafe), significant residual movement at connections, or major settlement approach, vertical offset of the abutment, differential settlement at connections, shear key failure at abutments, extensive scour of abutments or submerged electrical or mechanical equipment.
Complete	Any column collapsing or connection losing all bearing support, which may lead to imminent deck collapse, tilting of substructure due to foundation failure

This method focuses on describing the damage extent of the different structure components after disaster events. This model estimates the reliability and stability of the whole bridge by evaluating the different bridge structure components. While applying this method, performance groups are introduced to help evaluate the damage condition of the bridge structures. A performance group is a collection of discrete damage states associated with different structural elements. They are correlated because these components work together to transfer loads and need to be repaired together. Performance groups (PG) are applied to avoid double accounting (Mackie, Kevin Rory, Wong & Stojadinovic 2008). Estimating the repair costs benefits from the application of performance groups. Once the quantities for each performance group can be determined, the total amount of the same repair item across all performance groups can be computed (Figure 2.3). Otherwise, performance groups allow a more meaningful assessment. Decisions and estimations can be conducted independently for each performance group.

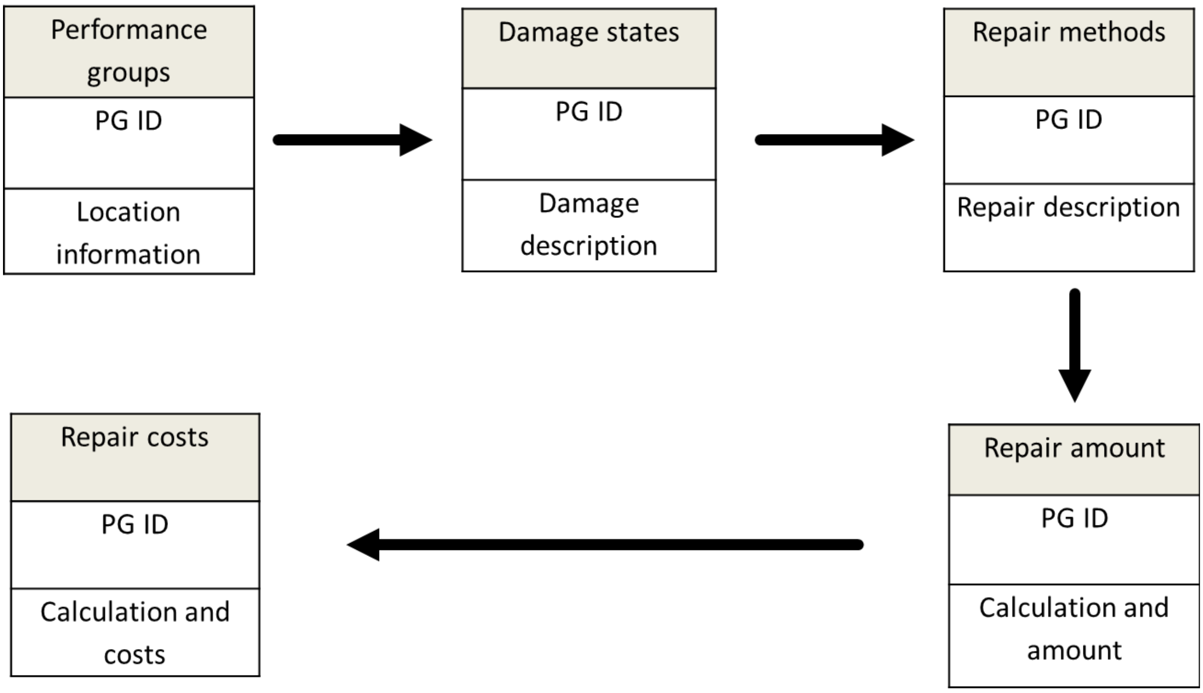


Figure 2.3 Use performance groups to estimate repair costs

Compared with all three methods, the third method has obvious advantages: First of all, this model has been validated by the estimated costs of bridge repair. The first method is introduced for bridge inspection, and it concerns more about bridge strength and safety. When the bridge is proved to be not safe enough, other inspections would be used to estimate the exact damage on the bridge. The second method is applied to estimate losses of all properties in flood affected regions including bridges. For estimating single bridge, the method is not as detailed as the third one. Secondly, the third method is more suitable to describe the damage states of a single bridge. It includes all aspects of estimating repair costs of single bridge damages. By setting performance groups, a more meaningful assessment of bridge damage, bridge strength, and bridge repair costs could be performed.

In terms of bridge damage states and bridge performance groups, there are difference between bridge types. The damage description for timber, concrete and steel structure would be different. For concrete, description would focus on crack, spalling and other types of damage. For steel structure, the damage states would relate to deformation and fatigue. In their 2010 research, Mackie, KevinR, Wong and Stojadinović detailed classified different damage levels of concrete bridges (Mackie, Kevin R, Wong & Stojadinović 2010). In terms of timber and concrete brdige, detailed description and standard are still lacked regards to different level of damage. This research would introduce damage states and performance groups of concrete brdige due to current knowledge gap.

2.3 Model review

Currently, different models have been developed to estimate economic impacts of flood events. However, these models cannot estimate all types of economic impacts. The majority of the models were established for one or certain kinds of economic impacts. Some efforts would be needed to integrate different models to estimate more economic impacts that are caused by flood events. However, the main problem here is that the scopes and definitions in different models are inconsistent. They cover different aspects and are sometimes overlapped. In Hallegatte's 2014 model, indirect losses include business interruption costs due to destroyed machinery. However, business interruption because of destroyed machinery is counted as an independent loss item in another research (Penning-Rowsell, E & Fordham 1994; Penning-Rowsell, EC & Wilson 2003). Actually, the business interruption is often referred to "as primary indirect damages because the losses do not result from the physical damage to property but from the interruption of economic processes" (Smith & Ward 1998). Before measuring different economic effects, models should be modified so that these models can be used to estimate losses and avoid double-counting.

In terms of economic impacts that are related to bridge damage, different types of models would be reviewed. These models cover bridge damage repair, debris disposal costs, the value of a historical building, costs for detouring, and business interruption. Comparing and choosing a proper and available model are important to estimate impacts correctly and avoid double-counting.

2.3.1 Bridge repair costs

In this research, the research objects are bridges and their damage in flood events. All types of losses should be caused by bridge damages, which is different from research that concentrates on impacts that are caused by natural disasters directly.

The definition of the direct cost varies in different models and research reports. Some reports described direct losses as the stock loss, which calculated all the repair and replacement costs involved in restoring activities after disasters (Fujimi & Tatano 2012). The mainstream disasters research institutes defined the direct costs as the expenses that will occur due to disaster events. However, the specific category in the direct cost will be different due to different research purposes. In CONHAZ flood reports, the disruption of production directly affected by the flood events and calculated as direct effects (for example, if the workplace cannot be reached) or the direct cost (Bubeck & Kreibich 2011b; Queensland 2002). However, according to the research on the economic impact of road infrastructure conducted by CRC Australia, the fact that the workplace cannot be reached was classed as an indirect cost. In this research, direct costs in this research would only focus on bridge recovery and debris clearance. This research would not cover vehicles that are damaged on the bridge.

Regarding bridge repair costs, there are controversies on cost measurement. There are two types of methods of cost evaluations: replacement cost and the depreciated cost of damaged assets. Replacement cost assumes damage goods and services will be replaced equal to the original with the full amount of the property value. This hypothesis of full replacement is not suitable to the real condition. Full replacement cost will overstate the losses because the value of the assets is depreciated. Another condition that could happen is that the bridge could be better than its pre-disaster condition. In some cases, repair and reconstruction of damaged structures will have some improvement after flood events (Penning-Rowsell, EC & Wilson 2003). There is another shortage of full replacement costs. The full replacement cost assumes the damaged assets will be replaced by a new one. That mostly leads the estimation results to be higher than they should be. Sometimes, the replacement costs are occasionally cheaper than the repair of the goods in their original condition (Merz et al. 2010). The majority of these models use replacement costs instead of depreciates because depreciates should consider conditions of each property due to life cycle.

Both replacement cost and the depreciated cost would like to replace the whole structure component with the full amount of the property value. In a real situation, a damaged bridge structure can be repaired, and repair costs would be cheaper than the full amount of the bridge structural components. The more accurate way is to measure repair/replacement costs due to the damaged conditions of the bridge. An ideal way is to align repair/replacement costs with damaged states, repair methods, construction materials, and size of damaged structures.

Table 2.5 Estimate the direct damage that is caused by flood events

Estimation direct costs of bridge damage in flood events						
Model name (Reference)	Country	Relative/ absolute approach	Empirical/ Synthetic data	Economic sectors covered	Loss determining parameters	Data needs
Model of multi-coloured manual (Penning-Rowsell, E et al. 2005)	UK	Absolute	Synthetic	Residential and commercial properties, leisure and sports facilities, public buildings, infrastructure	Water depth, flood duration, building/object type, building age, social class of the occupants, warning time	Values of exposed assets, socio-economic information, hazard characteristic
FLEMOcs models of (Kreibich, Heidi et al. 2010; Seifert et al. 2010; Thieken et al. 2008)	Germany	Relative	Empirical	Residential buildings, public and private services, producing industry, corporate services, trade	Water depth, contamination, building types, quality of building, precaution, business sector, number of employees	Values of exposed assets, residential buildings and company characteristic, hazard characteristic
Anuflood (Dutta, D, Herath & Musiake 2003)	Australia	Absolute	Empirical	Residential and commercial properties, infrastructure	Water depth, object size economic sector, object susceptibility	Property characteristics, water depth
RAM (Sturgess 2000)	Australia	Absolute	Empirical synthetic	Buildings, agricultural areas, infrastructure	Object size, object value, lead time, flood experience	Object characteristics, land use, warning times, flood experiences, season
Model of MURL (Merz & Thieken 2009; Thieken et al. 2008)	Germany	Relative	Empirical	Residential and commercial properties,	Water depth, economic sector	Land use data, values of exposed assets, water depth

				infrastructure, agriculture forestry		
Model of Hydrotec (Emschergenossenschaft 2004; Kreibich, Heidi et al. 2010)	Germany	Relative	Empirical	Residential buildings, commerce, vehicles, agriculture, forestry, infrastructure	Water depth, business sector	Land use data, values of exposed assets, water depth
HAZUS-MH (Vickery, Lin, et al. 2006; Vickery, Skerlj, et al. 2006)	USA	Relative	Empirical synthetic	Residential buildings, commerce, infrastructure, agriculture, vehicles	Water depth, flow velocity, wave action object type, riverine or coastal flooding	Object type, land use data, hazard characteristics
MEDIS Model (Förster et al. 2008)	Germany	Relative	Empirical synthetic	Agriculture	Flood duration, crop types, season	Market prices of agricultural goods, planted crop types, flood characteristics
HIS-SSM (Kok et al. 2005)	The Netherlands	Relative	Synthetic	Residential and commercial properties, agriculture, infrastructure, nature recreation, vehicles	Flood depth, flow velocity economic sector	Values of exposed assets, socio-economic data, land use, hazards characteristics
Schwarz and Maiwald (Maiwald & Schwarz 2010)	Germany	Relative	Synthetic	Residential properties	Water depth, flow velocity, structural characteristic	Information on building structure, land use data, hazard characteristics
Model of LFUG	Germany	Relative	Empirical synthetic	Building, mobile, immobile inventory	Water depth, specific discharge,	Values of exposed assets, information on building structure, hazard characteristics

The parameters typically used in these models were mainly factors used to describe the flood disasters and the types of the buildings, including the inundation depth, velocity, duration of inundation, contamination, debris/sediments, and the rate of rising (Kato & Torii 2002; Kreibich, Heidi & Thieken 2009; Thieken et al. 2008). In some models, even the design resistance to the flood were considered, for example, the building types, building material, precaution, external response/emergency measure, and early warning (Penning-Rowsell, E et al. 2005; Penning - Rowsell & Wilson 2006; Schwarz & Maiwald 2008). These parameters worked when measuring the average damage condition of bridges on a regional level. For a single bridge, research still concentrated upon force analysis and potential damage. A prediction for a single bridge damage would not be accurate. Aligning bridge damage with parameters has considerable uncertainties and bias. An estimation for 4000 damage records showed that a damage model would make a result of under or over estimation (Merz et al. 2004). In this research, these models are hard to apply due to problems of accuracy. However, they pointed out ways to measure bridge damage accurately.

To sum up, all models were based on the empirical or synthetic analysis of the floods data. Empirical approaches would use related parameters to estimate losses due to previous data (Merz et al. 2004), while the synthetic models allowed experts to use related parameters to estimate the amount of damage on structure components during floods. For a single bridge the empirical damage models are more suitable than the synthetic models at this stage. Compared with synthetic approaches, empirical approaches use detailed data surveys after disasters. Survey could provide more detailed damage information of a brdige. Synthetic approaches are based on estimating damage grade of building structures after disasters (Gissing & Blong 2004). Both analyses were based on a certain number of damaged objects. For a single bridge, both empirical and synthetics should face uncertainties that will impact damage conditions and repair costs after flood events.

Generally, two methods were used to measure the monetary loss of direct damages on the bridge: absolute and relative damage. Absolute damage means using the damaged structure elements aligned with the monetary terms; the estimation were derived from the flood results directly (Messner 2007). However, the relative damage correlates the damaged components with the portion of the maximum assets value of the whole building (Bubeck & Kreibich 2011a; Messner 2007). It is a part of the gross value of the building. In Australia, the direct cost models are mainly based on the absolute damage, for instance, the Anuflood and RAM models that were developed by different institutions in QLD and VIC (Queensland 2002; Sturgess 2000). These two models also give a solution to quantifying the indirect losses after flood events. In this model, the interruption of business, non-provision of public service and clean-up cost are defined as a fixed ratio of direct losses. Obviously, results of indirect losses in these two models are not fully explored and not accurate.

In this research, the absolute damage is still a suitable way to describe damage to the bridge. For measuring damage states of a single bridge, absolute damage could evaluate a more detailed and accurate result, whereas aligning bridge damage with parameters may lead to under or overestimation. In the study conducted by Kevin R. et al (2007), they pointed out that combining inspections and quantities could provide accurate results for estimating repair costs and recovery time (Mackie, Kevin Rory, Wong & Stojadinovic 2008). Also, performance groups were used to help calculate repair cost after inspection.

2.3.2 Value of historical bridge

Despite assets value, some bridges can be considered heritage due to their special cultural significances which mean its aesthetic, historical, scientific, social, or spiritual value for past present, or future generations (The Allen Consulting Group 2005). These bridges have non-market values. Different methods could be used to measure the intangible value of historic buildings. The most well-known method is to conduct a survey to measure willingness to pay (WTP) and willingness to accept (Mitchell & Carson 1989). Total WTP is the product of the average or mean WTP multiplied by the regional population. With the up to date development of economic theory and social survey methodology, more accurate methods have been introduced to the estimation of economic impacts that are absent of market values. Some methods can be reviewed:

Table 2.6 Intangible values of heritage buildings

Classification	Methods	Source
Revealed preference methods	Hedonic price method	(Bedate, Herrero & Sanz 2004; Choi et al. 2010; Ruijgrok 2006)
	Travel- cost method	(Brown Jr & Mendelsohn 1984; Choi et al. 2010; Poor & Smith 2004)
	Maintenance cost method	(Poor & Smith 2004; Ruijgrok 2006)
Stated preference	Contingent valuation method	(Dutta, M, Banerjee & Husain 2007; Lee & Han 2002; Tuan & Navrud 2007)
	Choice modelling	(Choi et al. 2010; Morrison, Bennett & Blamey 1999; Tuan & Navrud 2007)

In Australia, research and evaluation activities were organised by the Heritage Chairs and Officials of Australia and New Zealand to measure the value of the heritage conservation in Australia in 2005 (Ruijgrok 2006; The Allen Consulting Group 2005). During this period, the different literature and methods were reviewed. It summarized shortages, advantages, and achievements. Surveys and standards were introduced by the Heritage Chairs and Officials of Australia and New Zealand. There would be evaluations of the heritage value for historical buildings all around Australia. Taking this survey has been considered out of the scope of this research. Therefore, it is considered to obtain the results from the Heritage Chairs and Officials of Australia and New Zealand when a heritage building is damaged.

To estimate the value of a historical bridge, comments should be used for describing its characters. It is important to point out what makes this bridge distinctive. For a historical heritage, values are mainly from its humanistic value, history and designing of the bridge

(Navrud & Ready 2002). In this circumstance, comments about the bridge should include a short summary of cultural humanistic value, history, and designing.

2.3.3 Indirect cost

In terms of indirect losses, different papers and studies on natural disasters have different specific definitions and coverage. The majority of present studies define indirect economic impacts included all impacts resulted from the disaster itself (Rose 2004). Indirect impacts covers secondary consequences that are resulting from natural disasters. Instead of indirect impacts caused by natural disasters, this research focuses on indirect economic impacts caused by bridge collapse after flood events. Indirect impacts would be different from impacts that are caused by flood events. Compared with broad impacts caused by natural disasters, this research would focus on losses that are caused by change of access. These consequences could be extra traveling distance and time, delay of recovery and input and output that may occur due to the damag of bridge.

In terms of measuring indirect losses, common methods include a firm/household level survey, specific explanatory factors to explain the interaction of different economic sectors (Input-output model), and the markets and price changes (CGE model). These methods try to identify particular relation or mechanism in the economic system to estimate potential indirect economic losses. Indirect losses of road infrastructure disruption would mainly concern problems of lacking accessibility after bridge damage including adverse effects on both the residents and the local business.

To the best of the author's knowledge, all assessment approaches are mainly based on the three types of models: input-output models (I-O models), computable general equilibrium (CGE) models, and hybrid models. The I-O model allowed to estimate the impacts from an economic sector on other economic sectors. For the I-O model, there is fixed relation between the input and output. The I-O model is based on the assumption that lack of inventory, including technology, workers, materials, and production conditions, cannot be substituted.

Therefore, lack of input will finally affect the output. The shortage of this model is that estimation results will be higher than economic losses due to the lower flexibility of the markets and production progress. Rose notes that the model as "Criticisms against I-O pertain mainly to the inflexibility of the model's fixed coefficients, its static nature, and its equilibrium orientation" (Rose 2004). The model ignores the interaction between consumer, lost wages, profits incomes and reduced employment.

The CGE models analyse the change of the markets and price changes after disasters. They use the supply and demand relationship to connect all the agents including households, businesses, and government institutions in an economy. The supply and demand relationship of goods and services will be modelled (Narayan 2003). Therefore, change in the goods and services can predict effects on regional economy performance. This model provides enough flexibility and substitution. Actually, it assumes the market will function perfectly after the disaster, though this kind of market does not exist. That means it will have a lower result of estimation and be hard to apply (Meyer et al. 2013).

The Hybrid model is between these two models. It will either introduce factors to improve the flexibility of the IO models, or reduce the substitution elasticity of the CGE model. These models are an improvement of the IO and CGE model. These models emphasize using one or more relations to reveal economic impacts after disaster events.

All models face similar problems. These models are constrained by available, detailed and reliable data (Merz et al. 2010). These types of models would need a significant amount of data collected from different social sectors to make an accurate estimation. In addition, evidence illustrated that the indirect effects are more important in the major disasters than in smaller ones (Hallegatte 2008). In larger disasters, the main social resource would focus on disaster relief and recovery. Detailed records are hard to derive. Sometimes, records that are collected from different institutions are different.

Table 2.7 Indirect losses models

General Method	Specific Method	Application examples
Event analysis	Surveys at firm level	(Boarnet 1996) (Tierney 1997)
	Surveys at household level	(Gissing & Blong 2004; McCarty & Smith 2005)
Econometric approaches	Gross regional domestic product effect assessment	(Cavallo & Noy 2009) (Strobl 2011)
	National Gross domestic product effect assessment	(Albala-Bertrand 1993) (Cavallo & Noy 2009)
Input-Output analysis	Input-Output Models	(Hallegatte 2008) HAZUS-E (McCarty & Smith 2005) (Haimes et al. 2005) (Okuyama, Hewings & Sonis 2004)
Computable General Equilibrium Analysis	Computable General Equilibrium Models	(Berrittella et al. 2007) (Boyd & Ibarrarán 2009) (Horridge, Madden & Wittwer 2005) (Wittwer & Griffith 2010)
Intermediate models	Hybrid Input-output/Computable General Equilibrium Models	(Hallegatte 2014) (Rose, Oladosu & Liao 2007)
Public finance analysis	Analysis of the impact on public finance	(Mechler, Linnerooth-Bayer & Peppiatt 2006)
Idealized models	Modeling interactions of hazard impacts with technical change or business cycles	(Hallegatte & Dumas 2009) (Hallegatte & Ghil 2008)

In all these models:

(1) Event analysis is based on survey. It is good to collect information about losses after disasters. However, it is difficult to explain business losses due to transport inconvenience.

(2) Econometric approaches, Computable General Equilibrium Analysis, Intermediate models and public finance analysis focus on the gross change of local economy and finance. It is hard to measure economic impacts that are created by a single bridge.

(3) Idealized model, which is a type of input-output analysis, allows use transport as a factor that would impact the productive capacity of the business. In idealized input-output model, companies and industries rely on sufficient stocks of essential productive factors to maintain normal productive capacity. Essential productive factors are materials, gas, power supply and workforces. All these productive factors rely on road infrastructures. Productive factors that would have moved via bridge can be used as stocks to estimate decreasing productive capacity.

2.3.4 Loss of the accessibility

It is important to measure the value of accessibility provided by the bridge. During bridge clearance and bridge repair, bridge accessibility would be impacted. There would be two circumstances: complete bridge closure or a closure that is partly open to the public. Both consequences would lead to detours or traffic delay. The economic loss of detours and traffic delays can be measured as extra travel distance and extra travel time. A case study used extra travel distance and extra travel time to measure losses of the 58 Highway break down (Negi et al. 2013). To estimate extra travel distance and extra travel time, two types of data are needed. First of all, detour routine and ratio of each alternative road are required. Secondly, estimation of detour losses mainly depends on the availability of average daily traffic (ADT) data (Negi et al. 2013). Regional vehicle operating costs for each type of vehicle would be a good solution to estimate detour costs of vehicles.

2.3.4.1 Regional road system

In order to identify alternative roads and measure extra travel distance and extra travel time, a map can group different types of roads and measure traveling distance, and traveling time is needed. GIS map provides a solution for building maps for analysis (Ghose, Dikshit & Sharma 2006). It provides solutions to build up and marks maps for research and analysis purpose. Arc GIS road information system is introduced in this research. In this software, different road types, post-disaster conditions, the ratio of a detour, residents, farms, businesses, main services, daily destinations, etc. would be summarized and reflected in regional maps.

Regarding calculating extra traveling distance and extra traveling time, Google map provides a solution to estimating an ideal traveling time in ideal road conditions.

2.3.4.2 Regional vehicle operating cost models

The vehicle operating cost plays a major role in debris transportation and detours after natural hazards. The components of vehicle operating costs can be mainly concluded as the fuel consumption cost, tire cost, maintenance and repair cost, oil consumption cost, and capital depreciation costs (Berthelot, CF et al. 1996). Some other fees like the license, insurance, and the operator wages vary due to regional policy and regional salary level. In these models, saving traveling time and accidents are less likely to be considered (Thoresen & Roper 1996). Most of the studies about vehicle operating costs were finished at the end of 20 century by different institutes (Table 2.8). Some other models, such as the aaSIDRA (1984) model, were enhanced to add the estimation of the pollution and gas estimation in 2003 (Akcelik & Besley 2003).

Both the AUSTROAD (1994) and the New Zealand (1989) developed their regional model to measure the operating costs (Bennett 1989). In these two models, the traveling speed of the vehicles was vital to measure the fuel consumption in the different models. The estimation results were quite different in the different speed limits. One of the widely used models is HDM IV, which was developed by the World Bank. However, this model needs extensive data to support the estimation (Kerali, McMullen & Odoki 2000). Compared to HDM IV, the Canadian government proposed a mechanistic (PVOC) model, which had fewer parameters and support data. Also, this model was not be impacted by the traveling speed, and it was easy to operate.

Table 2.8 Models of vehicle operating costs

Model	Source
Operating cost, fuel consumption, and emission models in aaSIDRA and aaMtion	(Akcelik & Besley 2003)
HDM-IV application guide	(Kerali, McMullen & Odoki 2000)
Review and enhancement of vehicle operating costs models: Assessment of non-urban evaluation models	(Thoresen & Roper 1996)
Mechanistic-probabilistic vehicle operating cost models	(Berthelot, CF et al. 1996)
Road user cost determined from engineering first principles	(Berthelot, C 1992)
The New Zealand vehicle operating cost model	(Bennett 1989)

The PVOC model which is proposed by the Canadian government is considered to be the most suitable model for this research. This model considers fuel consumption cost, tire cost, maintenance and repair cost, oil consumption cost and capital depreciation costs (Berthelot, CF et al. 1996). Compare to other existing models, this model requires fewer data. Moreover, these data are relatively easy to collect. Secondly, this model is easy to operate and avoids sophisticated statistical analysis. It has fewer parameter than any other models. It can decrease the data collection problems. Another advantage of this model is that the majority of the parameters could be adjusted by local vehicle data. Therefore, the results will be more accurate because the vehicle constitution and average values are different due to preference, road condition and requirements.

2.3.5 Some other economic losses and estimation methods

There are some approaches which are developed to estimate the economic impacts of road infrastructure and bridge collapse could also be used to improve accuracy of this research:

(1) In the estimation of the Mississippi River bridge collapse, the research focuses on the travel demand change and the reaction of travellers(Xie & Levinson 2011). According to survey, most residents (92%) would not cancel their daily trips after the bridge collapse. The majority of people would adjust their departure time and daily schedule. This research provided solid evidence that majority stakeholders of the bridge would not cancel their trips. Travellers could use other paths, and traffic flow would be diverted to alternative roads. Also, this research compared traveling distance and traveling time. Detour choice would impact the surrounding road networks. It would increase the traffic pressure of alternative routes. Traveling efficiency of the local community would decrease (Xie & Levinson 2011).

(2) In the research carried out by Kevin, Mackie, etc in 2009 (Mackie, Kevin R, Wong & Stojadinović 2010), they provided an approach to estimate repair cost and repair time needed for a bridge with improvement after the earthquake. This research related bridge damage and repair period. Both repair cost and schedule were linked with unit costs and repair quantities.To illustrate this model, a detailed example of a reinforced concrete highway bridge was applied. This assessment provided higher level information to help decision-making after disasters. Besides, it had a clear schedule of recovery and can contribute to predicting how long the negative economic impacts would take. This model provided the experience of inspecting, setting performance groups and describing damage states. It also gave a basic solution for estimating repair quantities (Mackie, Kevin R, Wong & Stojadinović 2010).

(3) In thier 2009 research on bridge damage after hurricane, Padgett et al. analysed the damaged structural components of a bridge (Padgett et al. 2008). It compared the difference between hurricane and earthquake damages and explored the correlation between damage state and storm surge elevation. This research applied the damage state method developed for earthquake damages. It illustrated that damage state methods could be used for different types of disasters. Though causes and stress are different in various catastrophes, damages could be

similar (Padgett et al. 2008). In this research, damage states methods could be based on these two damage states methods.

(4) In their 2001 research, Sungbin and Peter introduced structure performance groups, transportation networks model, spatial allocation model, and inter-industry (input-output) models. This model attempted to reveal the relationship between the transportation system and the urban economy. This model focused on exploring industrial capacity and transportation demand and supply after the earthquake (Cho et al. 2001). This research combined regional transportation network, traveling routines, and transportation demands. It provided a valuable example of integrating models from different social sector to estimate economic impacts caused by bridge damage.

These models focus on various aspects of the economic impacts: the state of the damage grade, repair time, traveling demands and alternative roads and interruption of business caused by the bridge collapse. These models give examples combining different research models to estimate specific economic impacts that are caused by road infrastructures. However, these studies also illustrated main constraints of current knowledge and data collection.

2.4 Conclusion

2.4.1 Limitations and challenges of current research

Economic losses after natural disasters are concerned by different countries, institutions, and research practitioners. Lots of studies have already focused on assessing one or some types of economic impacts. In different types of research, various economic impacts, for example, effects on surrounding road networks, residents, local businesses and psychological problems have been mentioned and discussed. Some of the studies have already tried to use current knowledge to estimate economic impacts caused by flood events. However, these models have both their advantages and disadvantages. Accuracy and flexibility are the two main problems of these models. The results from the different types of model vary a lot. The majority of these models are not validated and constrained by data. Also, research on the different disasters is unbalanced. Currently, seismic models are more comprehensive, including the impacts identity, damage states, relationships between magnitudes and damage states, and the costs for recovery. Compared with seismic damage, models of flood events are not well developed due to the complex hydrology and mechanics of torrents. the majority of research still focuses on the correlation between flow stress and bridge damage. Less research has been done on the economic impacts of a concrete bridge that is damaged in flood events.

Some problems are revealed in the studies on bridge collapses in flood events. First of all, there are knowledge gaps for the damage mechanisms in flood events, which is due to the limits of the influencing factors and reliable data source (Merz et al. 2010). It is evident that current influence factors in assessment models cannot accurately predict bridge damage. Studies try to add more influencing factors to increase the accuracy and reliability of models. However, it is always hard to explore how these factors work and their effects (Merz et al. 2010). Secondly, economic impacts are not fully identified and systematically categorized. In previous research, economic impacts in flood events were mainly decided by the state of the knowledge and observations of research practitioners (Merz et al. 2010). Economic impacts that were summarized by different practitioners, institutions, and organisations have differences (Egorova, van Noortwijk & Holterman 2008; Wallingford 2000). Because of this, the different components of economic impacts in some studies might not be discussed comprehensively. Thirdly, models lack of invalidation and accuracy. Currently, different models were developed by different institutions. The majority of them were not well validated due to data constraints. As a result, these models still couldn’t get an accurate result. Fourthly, reliable, sufficient and detailed data are not enough (Merz et al. 2010). To meet data gaps, long-term tracking and observation of disasters events are still needed.

For indirect cost models, studies have determined the importance of understanding the indirect costs and intangible losses, but there is a lack of effective methods and tools to assess losses (Przyluski & Hallegatte 2011). The lacking available model happens to estimate in indirect losses of road infrastructure. Road infrastructure plays a unique role in many economic sectors. It is a fundamental part of the social economy. It influences almost all other economic sectors. However, effective methods are not available to help predict losses that are caused by road infrastructure failure.

In conclusion, there are still challenges on estimating impacts of bridge damage in flood events:

(1) Economic impacts of bridge damage are not fully recognized and understood. Majority of work based on knowledge and experience of researchers.
(2) There was a lack of accurate, detailed and sufficient data.
(3) Majority Research focused on regional or gross economic performance. Less research will focus on bridge damages and its economic implications.
(4) The majority of models were based on multiple buildings; fewer models focused on a single building and analyse its impacts. Also, existing models were often not validated.
(5) Lots of models and research focused on single sectors of economic impacts, for example, direct economic loss model, indirect economic loss model, detour, etc.
(6) Economic impacts, which were caused by bridge damage, were mentioned by different studies. However, these economic impacts were not well summarized and categorized.
(7) Available and reliable models were needed to measure economic impacts of bridge damages.

2.4.2 Model choosing

In this research, some of existing models mentioned above would be applied. The literature has achieved the following available models:

Bridge recovery costs include debris clearance and the cost to repair/replace damaged bridge structures based on inspection. This method had been discussed and applied (Mackie, Kevin R, Wong & Stojadinović 2010; Padgett et al. 2008). Compared with replacement costs and the depreciated cost, aligning repair costs with bridge damage states and repair methods would be more accurate. Replacement costs and depreciated costs would replace the damaged structure by the original one with the full amount of the property value. These two methods would not reflect the actual repair costs. Therefore, the estimating procedure in this research would apply performance groups and damage states.

The Costs of detouring would be another substantial expenditure when a bridge is either closed or partially open. This research would introduce Xie & Levinson' model to measure detour costs (Xie & Levinson 2011). This model integrates extra traveling distance and time to measure the additional cost. Before applying this model, alternative route and average vehicle operating costs should be estimated. In terms of alternative routes, this research would apply Arc GIS mapping to analyse regional road networks. For average vehicle operating costs, this research would use the model developed by Berthelot et al. (Berthelot, CF et al. 1996).

Business interruption is a secondary effect of bridge damage. Bridge damage can impact transportation and associated facilities such as power and internet connections around the bridge which could be relevant for the local businesses' productivity. In the research carried out by Hallegatte in 2008, he introduced inventory to describe the impacts on productive capacity (Hallegatte 2008). Transportation and associated facilities could be treated as stock. When the production resources and conditions did not meet business requirement, production capacity declined. This model allowed for the use of production resources that could be moved via bridge to measure the economic losses of business disruption.

CHAPTER3 METHODOLOGY

3.1 Research design

3.1.1 Purpose of the study

This research is a descriptive study. One of the main objectives of this research is to identify, clarify and describe the economic losses of bridge damage after flood events. It is a correlational study and will focus on identifying the economic impacts, defining their scope, and categorizing impacts by comparing and justifying previous studies. Another objective of this study is to introduce integrated methods to estimate economic losses of bridge damage after flood events. Finally, this research is intended to illustrate this model by applying it to a case study.

(1) In the current research, economic impacts of the damaged bridge have not been fully identified and justified. To understand losses of the bridge collapse, the first step of this research is to identify economic impacts of bridge collapse fully. This research should review previous work to summarize the economic impacts that are considered to be caused by bridge damage specifically. Also, all economic impacts should be sorted out into different groups. Up to the present, few studies develops proper classification groups for economic losses of the bridge collapse. According to current knowledge, all economic losses could be classified as direct/indirect and tangible/intangible. It is an efficient and necessary way to avoid overlap and double counting. This research would match each type of economic loss into different groups.

(2) Regarding assessment models, no existing model can cover and measure all economic losses of bridge damage that are caused by flood events. The solution is to combine different models to measure different types of economic losses. Different studies have already concentrated on working out certain kinds of economic losses. This research would review

and compare different types of models to measure economic losses of the bridge collapse in flood events. Before combining different type of models, some issues should be clarified and addressed: First of all, different models would have different definitions and scopes of losses. Some of these models focus on direct losses, while others may only concern detour after bridge damage. This research should measure scopes of these models and try to avoid overlap and second counting. Secondly, different types of models are based on different hypothesises. Previous models applied parameters to describe average damage conditions of buildings in a flood-vulnerable region. These models were based on a large number of samples. For example, applying empirical model to estimate the direct damage to physical assets after flood events. When it comes to a single building, the estimation will lose accuracy. This reasearch concerned with making sure that hypothesis can also be applied to a single bridge.

For a bridge, the local community is one group of the main stakeholders. Both local businesses and residents can get benefits from the bridge. After a flood event, the damage/closure of a bridge would impact the local community a lot. This study would like to induce current knowledge about the economic impacts of a bridge collapse in a flood event.Therefore, the local council and community can have a comprehensive view of what types of losses would happen to them. In addition, viable estimation methods could be introduced to help the local community to evaluate their gross losses due to bridge damage after flood events. To fully understand and estimate economic losses, a strategy could be advised to support the areas that would suffer the most economic losses.

3.1.2 Extent of researcher interference with this study

3.1.2.1 Minimal interference

As a correlative research on what are the economic consequences of bridge damage in flood events, the study also correlates different bridge damage extents with different types and amounts of economic impacts on the local community. This study relies mainly on reviewing previous work to summarize economic losses and proper models. This means analysing causes and effects to classify the different economic losses into direct/indirect and tangible/intangible. Evidence can be collected from previous disaster reports, research, and interviews. All work in this research has not interfered with normal activities of the local community. The researcher would not interfere with recovery of bridge. Research and researcher have minimal interference.

3.1.2.2 Non-contrived setting

In this research, recovery and rehabilitation work has been finished for years. Data are mainly relied on documents that were derived from the local council in Lockyer Valley - for example, disaster records, damage reports, inspection reports, repair plans, recovery plans, etc. Bridge damage states are derived from inspection reports and photos. Local traffic condition information is from traffic reports that were collected in 2006. Also, research will make a GIS map to mark road networks and identify alternative roads after road damages. These roads are identified from maps and road conditions are indicated by the fieldwork. Research can be finished in non-contrived settings with no interference with the post-disaster status of the local community. Also, the normal work routine of the local council and community are not impacted by fieldwork.

3.1.2.3 Unit of analysis

In this research, the research focus is an individual damaged bridge after a flood event. However, for each type of economic analysis, the unit of analysis would be different.

Regarding direct tangible impact, economic costs are costs of repaired/replaced damaged concrete bridge structures and debris clearance costs after flood events. For this purpose, research focuses on the damages on structural components of bridges and post-disaster debris quantities.Two types of data are required: One is the information about post-disaster conditions of each bridge’s structure component. The other is the debris quantity that needs to be collected. The unit of analysis is individual in this part.

Regarding the indirect tangible impacts, this research would explore accessibility problems that are caused by the bridge damage. Both residents and local business are stakeholders in the bridge. They need to face traffic and transportation problems. The research object is a group of stakeholders in the traffic-affected region. During bridge closure, both business and residents would need to change their routines and adjust their trips. All interested parties would suffer longer travel distance and more traveling time. Research needs to summarize changes of stakeholders' traveling distance and time. It requires group analysis of these interested parties.

For local businesses, detour is not the only economic impact to them. Bridge damage could also impact the productive capacity of the local businesses by impacting the transportation of supply. Some businesses rely on the bridge to maintain their productive material. Also, post-recovery of associated facilities, industries, and farms also rely on the bridge. Take cargos and related facilities as inputs, bridge interruption would threaten the output capacity of local business and industry. In this progress, different types of inputs should be summarized and analysed. A group of inputs should be treated as analysis units.

3.1.2.4 Constraints of data Collection

Data collection is still a problem in disaster research. Multiple studies have discussed the accuracy of disaster-related data. Lots of researchers pointed out that damage estimates for small events and local jurisdictions are often extremely inaccurate (Downton & Pielke 2005). At present, the accuracy of previous data is questionable and could not meet the requirements of disaster research. Further research needs more reliable, detailed and accurate data. Data collection and accumulation should be concerned in this research.

Data collection are also constrained in this research. Lots of valuable data could be gathered during bridge recovery. However, some types of important information are often ignored or not well-recorded. There are vary few studies on the tracking of bridge recovery. Post-disaster recovery always takes a long time and a considerable amount of costs. After flood events, road infrastructure and the bridge would be repaired immediately to recover access. Access is necessary to post-disaster rehabilitation. However, the recovery progress of the bridge could be limited by shortages of resources, such as professional workforce, materials, funds, etc. In addition, the design of the bridge would also take time to guarantee structure strength and safety. For the damage to be repaired, the bridge would need a more complex design than expected. For those reasons, the time limit for bridge recovery is difficult to predict. It may take more than one year in different conditions. To track the economic impact of bridge damage, various types of data would also be collected at different stages of bridge recovery. Data collection would also have a long time span.

This research would integrate different types of models to estimate economic impacts. These models cover multiple social sectors of the local community. There would be different data requirements for different kinds of models. Data would be obtained from different data resources. During data collection, it is found that not all data would be available and collected at all times. Some types of data have a clear time horizon. These data will not be available or will not be easy to obtain as time passed. Therefore, these data cannot be derived if they are not collected on time. Some kinds of data are ignored or not well recorded. In addition the time horizon, there are two other problems that would increase the difficulty of data collection:

(1) Few databases are available and have been developed for collecting, comprising and classifying so many types of relevant information related to bridge damage. Researcher cannot obtain required data from a database. Therefore, researchers need to introduce multiple data sources to obtain necessary data.

(2) Possibly, important information may not collected or ignored by the local council and other researchers. Institutions, governments, etc., could collect useful data to satisfy their own purpuse. These records may not perfectly satisfy the research objectives of other researchers. Sometimes, information may not be collected when the local council and researchers believed that these types of information are not important to them.

It is difficult to conduct research and produce a comprehensive analysis of bridge damage and its economic impacts if there is a data gap. In some studies, researchers have to depreciate their analysis because of a data insufficiency constraint (Merz et al. 2010). In order to solve the problem of data insufficiency, this study proposes the use of a time horizon and collection time for related data. This proposal could benefit both future research and local communities that need to collect data to estimate economic losses from a bridge collapse during a flood event.

After a flood event, data regarding bridge damage and debris quantities should be collected. Inspection reports can be a valuable and reliable information resource for evaluating bridge damage and debris conditions after a flood event. During a post-disaster inspection of a damaged bridge, debris samples can be collected, and debris quantity can be evaluated. However, very few reports would describe detailed information about debris types and quantities around the bridge. To estimate debris clearance costs, it is important to evaluate debris type and deposit quantity. On this circumstance, photos would be a significant help. For bridge damage and debris condition, detailed information are better to be collected before repair and recovery work. When recovery is finished, some data will not be easily derived due to changes of object condition and file management difficulties. Bridge damage conditions and debris quantities are information with strict time limits if a researcher needs to collect data personally. For post-disaster research and analysis purposes, these types of information could be derived from different kinds of documents. However, records from these papers could not totally satisfy research purposes.

Estimating impacts of bridge accessibility would include road networks, road conditions, traveling information, traffic information, and traffic constitutions. It would concern impacts on residents and local businesses by comparing differences between pre-disaster and post-disaster travel. It is important to collect enough data to conduct traffic distribution studies. These models need multiple types of data, and these data have a different time horizons. However, traffic conditions, road networks, population distribution, business location, and types of roads will not change a lot within a few years. For these kinds of information, time horizons are not strict. The majority of data can be collected by fieldwork personally. There are multiple ways to collect these data. Some types of data, such as the post-disaster condition of roads and detour routine, would be recorded during a bridge closure, partly opened and recovery period. These data have a clear time horizon. If these data can not be collected on time, they would not be available or very hard to collect.

Regarding the impacts on the productive capacity of the local industry and farm, three types of important data should be of collected. First of all, information about the recovery of the associated facilities are important. Power, water, internet and sewer lines would impact the surrounding industries and residents. However, the recovery of these associated facilities relies on bridge recovery. These types of data are recorded in the bridge recovery plan. Also, the supplier would have records of the rehabilitation and stakeholders. These data have obvious time limits. The availability of data sometimes depends on whether if the supplier wants to provide these types of information. Secondly, information about the amount of material that would be transported via the bridge should be recorded. These data would include two parts: The first part is material that would be delivered before the disaster events. The second type is material that can be transferred after bridge damage. The first type of data can be estimated before and after bridge damage. There are fewer limits on this type of data. The second type has strict time limits. Some recovery information, should be collected during bridge recovery. Also, during the different recovery periods, such as closure and partial opening, accessibility of the bridge would be different. Thirdly, accessibility can also impact the recovery of industry and farming. These types of data would be derived mainly by interviewing stakeholders after flood events. For these kinds of data, information should be tracked until the bridge gets recovered or the delay is eliminated.

Some other problems would also constrain data collection. First of all, disaster events are uncontrollable and complex. It seems impossible to design a data collection environment to get proper data. Also, these data are limited by time. Some disaster events would be several years old. That would increase the difficulties in data collection. Secondly, the data collected by different institutions for different purposes are detailed in different aspects and may not satisfy research purposes. Data in most of the studies are based on previous disaster documents, records, previous research and analysis reports about natural disasters. Few disaster studies can collect data personally and track whatever they need. To figure out the different types of data that are required for this research, a table is summarized in preparation for applying the integrated model (Table 3.1).

Table 3.1 Data collection and time limits

Type of losses	Model	Data required	Time limit	Collect time
Direct tangible losses	Bridge repair costs	Bridge damage condition and each structure damage condition	Strict time limits, also due to file management	Data should be collected after flood events Immediately. For these types of data also can be derived from inspection report and photos.
	Debris clearance costs	Debris constitutions and quantities including demolition wastes	Strict time limits	Should be collected after flood events. Accurate quantities are hard to be estimated and collected from relevant research, reports, and photos.
		Debris disposal and dump sites	No time limits	These types of information can be collected almost any time.
Indirect tangible losses	Roadmaps	Road network, road condition, traveling information, traffic information, traffic constitutions, population distribution and business location	virtually no time limits	These types of information could be collected after recovery. Majority types of data can get from maps, road agency, and related institutions
		the post-disaster condition of roads and Traffic condition of detour routine	Time limits	Information needs to be collected after flood events. Data need to be tracked.

<table>
<tr><td rowspan="5"></td><td>Regional vehicle operating costs</td><td colspan="2">Multiple parameters are required. Parameters are related to vehicle institution, vehicle types, etc.</td><td>No strict time limits</td><td>Parameters for different types of vehicles are summarized in the case study.</td></tr>
<tr><td rowspan="4">Productive capacity of local industry and farm</td><td colspan="2">Recovery of associated facility and stakeholder information</td><td>Not very strict time limit and due to file management</td><td>These data should be collected with bridge recovery plan. Most of the time, these types of data should get support from supplier and local council</td></tr>
<tr><td rowspan="2">Productive material that would come via bridge</td><td>Pre-disaster</td><td>No strict</td><td>Can be derived after recovery</td></tr>
<tr><td>Post-disaster</td><td>Strict time limit</td><td>Track data during bridge recovery</td></tr>
<tr><td colspan="2">Recovery of industry and farm</td><td>Strict time limit</td><td>Track data during bridge recovery</td></tr>
<tr><td rowspan="3">Direct intangible</td><td rowspan="2">Historical building</td><td colspan="2">Description of historical building</td><td>No strict</td><td rowspan="2">Get information from document and related institutions</td></tr>
<tr><td colspan="2">Value that is estimated by Heritage Chairs and Officials of Australia</td><td>No strict</td></tr>
<tr><td>Psychological impacts on bridge user</td><td colspan="2">Traffic support</td><td>Due to file management</td><td>Strategy, resource and support that are provided by local council</td></tr>
<tr><td rowspan="3">Indirect intangible</td><td>Loss trusts on authorities</td><td colspan="2">Human and social resource, public efforts that would be used to improve communication, the participation of residents.</td><td>Due to file management and tracking data</td><td>Tracking during bridge recovery and strategy from local council</td></tr>
<tr><td>Labour market change</td><td colspan="2">Job opportunity for local community and unemployment</td><td>Time limit</td><td>Government report and tracking data</td></tr>
<tr><td>Impact on surrounding environment</td><td colspan="2">Disposal standard</td><td>No time limit</td><td>These data could be derived from government report</td></tr>
</table>

3.2 Data collection

This research can be separated into three parts: (1) Identify and categorize the economic impacts that are caused by bridge damage in flood events; (2) Introduce and integrate the models to estimate and describe the economic implications; (3) Use a case study to demonstrate the models.

(1) This research will discuss different economic impacts of bridge collapse after flood events. Currently, few studies focused on analysing the specific economic impacts which are brought by bridge disruption in flood events. This research will summarize the different viewpoints that were mentioned by experts in their research. Review scopes will include research on flood events, bridge damage reports, post-disaster interviews, post-disaster reports and road infrastructure reports.

The classification of the economic impacts will be different from the disaster analysis. In the disaster analysis, direct impacts are caused by the flood events and indirect impacts are secondary impacts that are caused by the flood events. In this research, the direct economic impacts are costs that are caused by the bridge damage. The indirect costs are secondary impacts that are caused by the bridge damage. In order to classify economic impacts clearly, a cause and effect analysis needs to be conducted to distinguish direct and indirect economic impact.

(2) The second part would introduce some existing models to estimate different types of economic impacts. Economic impacts that are resulted from a bridge collapse would involve different social sectors, such as damage recovery, traffic problems, daily activities, collective activities, business disruption, etc. This research would focus on economic impacts that could be measured by monetary value. For intangible values, this research will use descriptive methods to interpret economic losses. In model development, this research attempt to provide a solution for the local council and stakeholders to estimate losses due to different damage

states of the bridge. Existing models that have been validated and could be applied straightforward would be put in first place.

(3) The third part of this thesis would apply integrated models to a case study to illustrate these models. This flood event happened in 2011, and there was bridge damaged in that event. This case study is based on the secondary data that are collected after flood events by the local council. Quality and reliability of data would constrain the accuracy of estimation results. First of all, this case study would need to collect evidence from different social sectors that would rely on bridge and transportation. Integrated models would need to collect data that are involved in different social sectors. For example, damaged information about the bridge will be collected from the local council, while the regional vehicle operating costs need data from road agency. Obviously, some types of information which are in this research were not recorded by the local council. This creates difficulties with collecting data from other areas and institutions to support this case study. Other data sources, which could not be derived from the local council, would be introduced to collect necessary data. These data are derived from different resources, including disaster records on the internet, case studies, disaster reports, inspections and repair reports, previous research, and published information. Another problem is that the majority of data that would be used in this case study were either collected or summarized by other research practitioners and institutions. Data collection standard would be different for different purposes. There are also different standards for different institutions to collect their data. For most media reports and insurance companies's reports, direct losses of property would only partly cover assets damage. For instance, the insurance company would only calculate damages that are covered by the insurance clause. The accuracy of their results would be concerned. Therefore, records by media report and the insurance company could not satisfy the requirement of most of the studies (Gentle, Kierce & Nitz 2001). In order to benefits future studies' data requirement, more efforts should be made to obtain high quality and detailed disaster records. However, the majority of the recovery work has been completed, so the researcher cannot track recovery progress personally to collect information for integrating models.

3.2.1 Data collection methods

Some data needs to be collected by fieldwork, for example, identifying the effects of bridge collapse after flood events. CRC conducted an interview in Lockyer Valley regarding the effects of loss of access. Most of the impacts that are caused by loss of access due to flood events have been identified and cited in post-disasters studies and interviews (Merz et al. 2010). These effects were observed or surveyed by research practitioners. Some of these impacts are from knowledge and experience of researchers (Setunge et al. 2015). After a flood event, access is one of the main problems that are of concern to residents. Access is described as livelihoods by the local residents. CRC's interview illustrated that damage to critical road infrastructure impacted residents (Setunge et al. 2015). As a critical facility that provides access to residents and businesses, a bridge outage creates significant economic impacts.

The CRC research group has conducted a series of studies on the road infrastructure affected by disaster events. Bridges were an important part of research on road infrastructure. The structured interview of the residents who lived in QLD (Queensland) provided information about their experience of flood events in 2010, 2011, and 2013. Questions were set to respondents to know their impression about three flood events, how road infrastructure damage affected their normal life and how flood events influenced the accessibility of road infrastructure. Accessibility and consequences in three flood events were compared. Also, the difference between three disasters were asked; for example, which flood event was more serious and which one affected their lives most? Their interpretation and description were separated and summarized as pre-flood, during the flood, and post-flood. The answers of respondents will provided information on how the damaged bridge affected the surrounding road networks and how a bridge closure affected residents. This interview involved their reactions and feelings to the very situation, especially the period that loss access to outside, including road closure, bridge collapse, no electricity and lost communication with the outside. This part could be used to analyse the direct intangible effects on the local community. Though it is difficult to be realized and measured, the psychological problems which are caused by traffic problems exists and have been noticed by some researchers. Although, this interview would mainly focused on impacts of accessibility after flood events, it also pointed out problems that resident and local council should face to after flood events. It also reflected that road infrastructure and their access to it were crucial to other types of infrastructure. Power, communication and internet connection recovery rely on road infrastructures heavily.

Regarding bridge damage states, information about bridge failure in flood events needs to be collected. There is a study of 383 recorded bridge failures and the Lockyer Valley Council provided 48 recorded bridge damage in 2011 flood events. They can be evidence to help summarize bridge damage states in flood events. This collection reviews the existing reports to collect bridge performance and damage information after flood events including damage position, damage state and repair cost. Different bridge structure components and their damage conditions after flood events were recorded by observers. These files are mainly used for analysing causes of bridge failures in flood events and bridge repair costs. It summarizes the frequency and ratio of different structure components in flood events. Also, it can be used to group different damaged structure components for performance groups.

Inspection reports and repair/bracing plans for damaged bridges would be important files to estimate bridge damage conditions. The purpose of inspection are is to check the reliability and stability of damaged bridge structures after flood events. For inspection, there will be a checklist and a guide for each type of damage. Inspectors need to follow rules and record practically everything that is observed. Inspections will check all aspects that can affect the reliability, stability and carry capacity with detailed information. If there are some severe damages, there will be a further inspection to estimate impacts on the whole structure. Therefore, these inspection reports can be used as detailed data to estimate damage condition of the bridge after disaster events. However, there are still variations between different inspection reports. There are two problems that will lead to variation. First of all, there will be the differences between different region and company. These variations are existing and inevitable in different institutions and areas until common standards are introduced and accepted by all businesses. Secondly, different inspectors may have different judgements about the same damage condition. Though there are detailed rules and evaluation criterions, they only minimize and cannot entirely avoid biases of observers. It could be considered that these variations will not affect the results of estimation. Rules and checking lists that promise results of inspection are comprehensive and conform to damage description. These variations under the damage description rules will be subtle. An experienced professional inspector will minimize description variation of bridge damage checking.

Data, such as traffic flow information, road condition information, parameters of the road material and surface, could be collected and recorded by a local council or road agency. Generally, a road agency would measure and record road and traffic information. These data are required by road agents to assess traffic conditions and improve the traveling experience. Therefore, road agencies and the local council should collect road information periodically. This type of information can also be used for this research. Regarding traffic flow information, these data are collected through mechanical observation. Details of vehicles that traverse bridges are tracked by video cameras at a crossroad. The tracking system keeps a record of the number of vehicles that travel via the bridge per day and the constitution of these vehicles. In data collection procedure, human interaction are not involved. Therefore, data collection is not affected by the preferences and biases of observers.

Traffic flow of domestic and business vehicles changes after bridge damage. There is a decrease in demand for traveling and an increasing demand for goods and materials transportation. According to a study of Mississippi bridge collapse, 90% of the resident would not change their trips in the event of a bridge closure (Zhu et al. 2010). That means traffic flow of residents will decrease by around 10 percent. Therefore, it can be explained that the majority of residents will continue their traveling but change their optimal path. Compared with the family car, heavy trucks and tool cars will increase in the disaster-affected region. These vehicles will serve clearance, repair, and construction work after flood events. If damaged bridge is the optimal path that accesses the local community, almost all transport carts would be affected. If the damaged bridge belongs to one of the main roads to the local community, increasing carrier vehicles could come from different areas. It is difficult to track how many carrier vehicles have to change their path because of bridge damage. In this research, it is assumed that the total number of the vehicles, which would come to use this bridge, will not change a lot before or after natural hazards. The real problem of traffic information is that the traffic record cannot meet the requirement of vehicle operating cost models. Vehicles that travel via the bridge can be separated into heavy trucks and normal vehicles. However, in the vehicle operating models, these vehicles can be divided into cars/light trucks, 2- & 3- axle farm trucks and 5-axle semi. The more detailed classification of vehicles, the more accurate the assessment of the operating costs for each group of vehicles. The decrease of classification will definitely affect the results of assessing.

The data regarding the quantity of production material that would come via the bridge were not calculated before bridge damage and during bridge recovery. This flood happened four years ago. A majority of the recovery work had been finished. It is impossible to track related data for this case study.

3.2.2 Main data source review

Required data and main data sources that would be used in this case study are as follows:

Table 3.2 Summary of required data

<table>
<tr><th>Type of losses</th><th>Model</th><th colspan="2">Required data</th><th>Data Source</th></tr>
<tr><td rowspan="3">Direct tangible losses</td><td>Bridge repair costs</td><td colspan="2">Bridge damage condition, each structure damage condition, repair methods</td><td>Inspection report, repair plan, design drawings, steel bracing drawings and photos from local council</td></tr>
<tr><td rowspan="2">Debris clearance costs</td><td colspan="2">Debris constitutions and quantities including demolition wastes</td><td>Photos and Opinion from local council by field work</td></tr>
<tr><td colspan="2">Debris disposal and dump sites</td><td>Local council
Maps
Australian government report</td></tr>
<tr><td rowspan="7">Indirect tangible losses</td><td rowspan="2">Roadmaps</td><td colspan="2">Road network, road condition, traveling information, traffic information, traffic constitutions, population distribution and business location</td><td>Google map, local council and road agent data
Road condition is checked with field work</td></tr>
<tr><td colspan="2">The post-disaster condition of roads and Traffic condition of detour routine</td><td>Local council provides information</td></tr>
<tr><td>Regional vehicle operating costs</td><td colspan="2">Multiple parameters are required. Parameters are related to vehicle institution, vehicle types, etc.</td><td>Australian Bureau of Statistics
RACV report
Vehicle Techs
Road Agent
Commonwealth report
Vehicle</td></tr>
<tr><td rowspan="4">Productive capacity of local industry and farm</td><td colspan="2">Recovery of associated facility and stakeholder information</td><td>Not available</td></tr>
<tr><td rowspan="2">Productive material that would come via bridge</td><td>Pre-disaster</td><td>Not available</td></tr>
<tr><td>Post-disaster</td><td>Not available</td></tr>
<tr><td colspan="2">Recovery of industry and farm</td><td>Not available</td></tr>
<tr><td>Direct intangible</td><td>Historical building</td><td colspan="2">Description of historical building</td><td>Not a historical building</td></tr>
</table>

		Value that is estimated by Heritage Chairs and Officials of Australia	Local council information
	Psychological impacts on bridge user	Traffic support	Local council information
Indirect intangible	Loss trusts on authorities	Human and social resource, public efforts that would be used to improve communication, the participation of residents.	CRC interview and local council information
	Labour market change	Job opportunity for local community and unemployment	Reports focus on empolyment change and not discuss the changes due to bridge access problems
	Impact on surrounding environment	Environment impacts of waste disposal	Environment and Australian government report

CHAPTER4 IMPACTS IDENTIFICATION AND CLASSIFICATION

4.1 Economic impacts identification

In previous research, different economic losses and costs of flood events are identified and discussed (Merz et al. 2010; Meyer et al. 2013; Setunge et al. 2015). Generally, these studies focused either on the regional economic impacts of natural disasters or impacts on the national economy. Most of the previous research considered regional gross cost for rehabilitation and decreasing gross domestic product while some models analysed fluctuation of the national economy and gross domestic product after disasters. In conclusion, current research focus on different economic aspects after disasters, including destructive effects on the local community, effects on daily lives, impact on regional economy performance, long-term effects on community and country, cost for recovery, evacuation and relocation after disasters, etc.

At present, some researchers focus on the damaged properties and economic loss after flood events. Some of the studies concentrate on estimating damaged properties in disaster-affected regions including bridges, houses and public buildings (Mackie, Kevin R, Wong & Stojadinović 2010; Padgett et al. 2008). There are also researches which focus on the average repair cost of bridge damage after disasters. In some studies, research practitioners try to associate parameters that are used to describe magnitudes with regional average repair costs(Jonkman et al. 2008).

Regarding indirect costs, there are I-O models and computable general equilibrium (CGE) models that focus on decreasing products or incomes to an economical level. However, far less research concentrates on one important infrastructure or analyses how necessary infrastructures will impact surrounding areas and other social aspects after flood events. In previous studies, the impacts and importance of bridge and other road infrastructures were discussed. These impacts were scattered in different papers, and there is a lack of further research on how to estimate these impacts. In order to figure out what these economic impacts are and how to estimate economic impact, a summary of previous studies should be conducted first.

In this research, the economic costs of bridge damage and its impacts on the local community will be explored and justified. The first step of this research is to screen out the impacts caused by bridge damage including bridge closure during the inspection and repair periods. Different researchers point out the importance of road infrastructure and the special status of bridges to the local community. Local community and other infrastructures, such as sewer, electricity supply, water supply, and the Internet, rely on road networks. Also, local residents have mentioned that damaged road and bridges affected their daily lives after flood events. As an important part of road networks, the bridge has a significant intangible value other than its construction cost (Hallegatte & Przyluski 2010) because it provides accessibility and affect almost all aspects of the community by connecting the road networks on its two sides. Its potential social value and the possible economic losses after flood events can be summarized into four categories: direct tangible costs, direct intangible costs, indirect tangible costs, and indirect intangible costs. This research will focus on identifying the economic impacts of bridge damage and classify different economic impacts from previous studies.

4.1.1 The main economic impacts of bridge damage after floods

After bridge damage, there would be different types of losses that could happen to 4 areas

1. Costs for accessibility recovery

The direct economic impacts of bridge damage are the expenditures on debris clearance and damaged structural component repair after flood events. Both debris and damage on structural components can impact the accessibility of the bridge:

(1) Clearance is an inevitable expense after flood events. Debris can be wastes accumulated by the water flow and construction wastes created during bridge recovery. Debris can build up on the upstream side of bridges and sometimes on the superstructure of bridges. Debris on superstructures can hinder traffic directly. Cleaning debris on the riverway and riverbanks can also occupy the motorway of the bridge. In some occasion, debris cleaning would close the whole bridge (Figure 4.1). Cleaning debris around damaged bridge would be also a preparation for execution conditions of repair work (Figure 4.2). Otherwise, some damaged bridge structure components need to be demolished for repair/replace. These construction wastes should also be cleaned. In Australia, there are specific guides for disposing of construction and demolition wastes. Generally, all debris and wastes need to be collected and transported to a designed location for disposal with innocent treatment (Çelik, Ergun & Keskinocak 2015; FEMA 2007). Debris that built up around the bridge and created during bridge construction needs to be collected to recover bridge access and prepare for repair work. The expenditures on debris clearance should cover debris collection, transportation disposal and intangible costs for its effects on the environment. According to a report of FEMA, expenses on debris cleaning could account for 27% of the total cost of disasters management (FEMA 2007). In this research, clearance costs would concern expenditures on cleaning all debris. Debris clearance includes costs that would be spent on recovering bridge accessibility, preparing execution conditions for repair work, and managing demolition and construction wastes

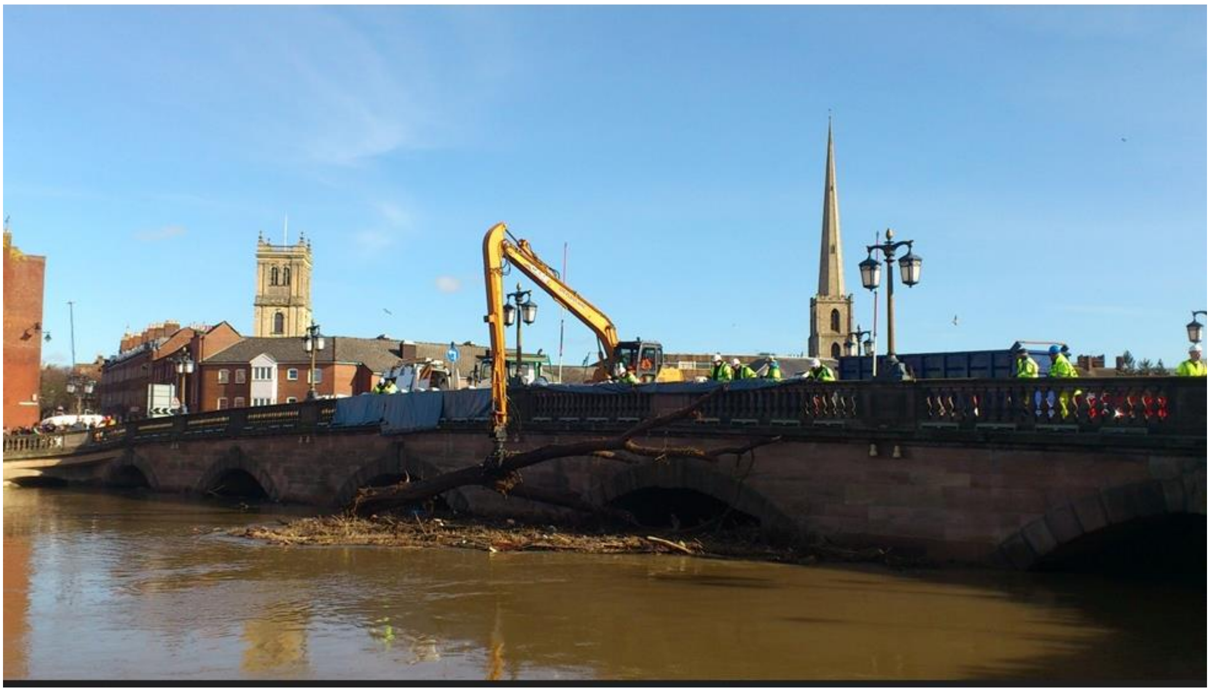


Figure 4.1 Closure bridge for debris cleaning (KATHERINE SMALE 2014)

Figure 4.2 Cleaning surrounding areas for repair preparation (A bridge on the Gladstone to Biloela road which damaged by floodwater associated with Cyclone Marcia. Picture: Peter Wallis)

(2) Bridges are one of the flood-vulnerable road infrastructures. 2010-2011 floods in Queensland had a huge impact particularly on central and southern Queensland resulting in 89 severely damaged bridges and culverts (Authority 2011). Different types of damage on bridge structure components can be observed after flood events (Figure 4.3). Any types of damage may decrease the strength of the whole bridge and impact accessibility of the bridge. A damaged bridge needs to be fully inspected, well designed and repaired to guarantee its strength.

Regarding gross costs of bridge recovery, expenditures are mainly for inspection, repair, replacement and reinforcement of the damaged bridge after flood events. They are inevitable costs to guarantee the strength and safety of a bridge. There are different factors that would impact costs on bridge recovery. First of all, repair costs also vary from structure types, building size, construction materials, designing, etc.

Secondly, bridges can suffer different types and extents of damage in different flood events. For different damage conditions, repair cost per unit is not fixed. Also, bridge damage states is an important factor to measure repair time.

Thirdly, when inspection shows that repaired bridge structures are not enough to guarantee bridge stability and reliability, there will be reinforcement to guarantee reliability and stability of the bridge. For example, additional steel bracing was used in the Kapernicks Bridge, which is also the case study bridge, to improve carrying capacity and stability of the bridge.

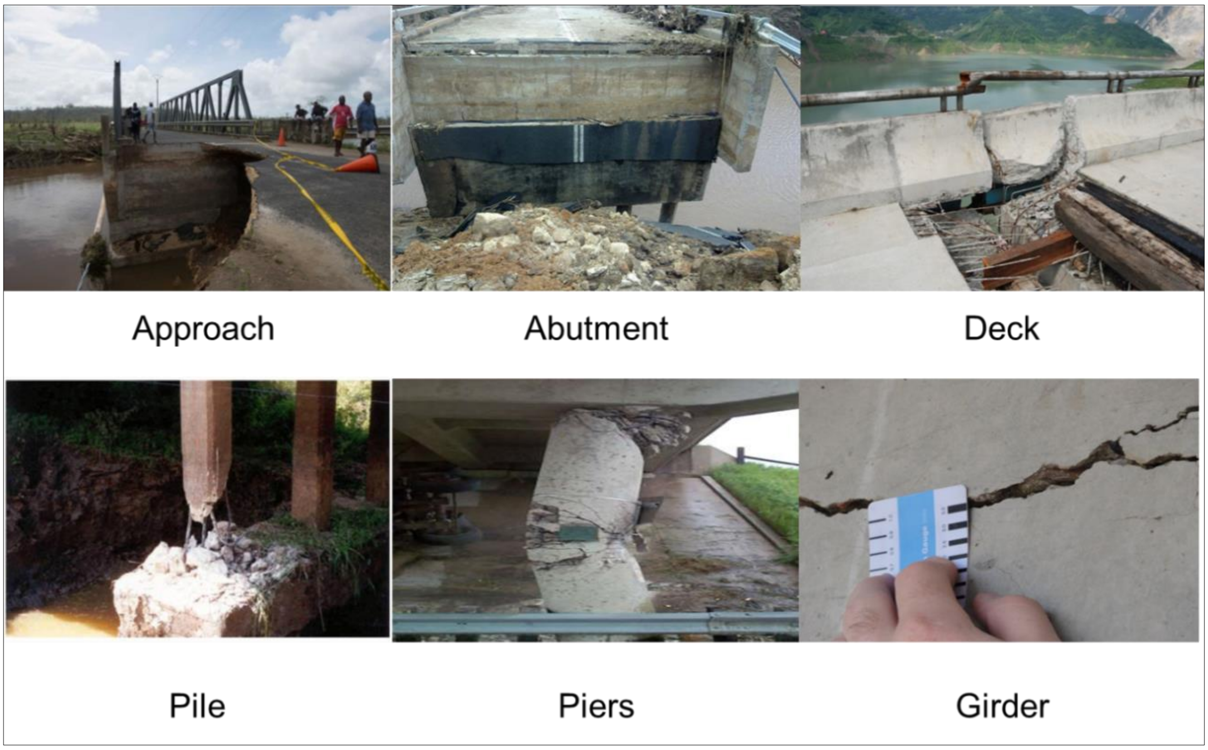


Figure 4.1 Damages on bridge in flood events (Lockyer Valley council)

It was assumed in the previous studies assume that repair costs were related to disaster characteristics such as flood depth, duration, velocity, etc. In this research, repair costs which are spent on different damaged structure groups are assigned to bridge damage states and inspection report. Secondly, some damaged bridge structure components will be replaced. Most of the time, damaged steel barriers and reinforced concrete slabs could be replaced by new ones. Similarly, some slabs of the Kapernicks Bridge also be replaced after the 2011 flood event. In addition to the bridge bodies being damaged in flood events, there is another circumstance that bridge bodies or structure groups are not damaged or slightly damaged, which will not affect the stability and reliability of whole the bridge. On this circumstance, the expenditures are mainly costs on debris clearance and bridge safety inspection.

2. Costs for bridge users and local industries

According to Queensland Government (Queensland Government 2015), four main reasons would lead to road closure after natural disasters: damaged, blocked, unsafe, and needed for emergency vehicles. Also, bridge users may not be able to use these roads until they are: checked by a road engineer, cleared, fixed, and no longer needed for emergency vehicles. Figure 4.3 shows that the local government closed AJ Wyllie Bridge after flood events in January 2011. During this time, the bridge would lose accessibility. After a flood event, there is a high possibility that bridge would be closed or partly opened to bridge users. That would lead to traffic delays, traffic congestion, and a detour to bridge users.

After flood events, Queensland Government would engage some private companies to undertake the necessary inspections. In Lockyer Valley, inspection work would be conducted by companies that are recommended by Queensland Transport Main Roads. The inspection decided whether the bridge was ready to open or it needed further inspection and necessary repair.

Figure 4.2 AJ Wyllie Bridge in Petrie, January 2011 (Queensland Government 2015)

When a bridge is closed or only partially opened to the public, two types of economic impacts on local community could be identified (Cho et al. 2001; Hallegatte & Przyluski 2010):

(1) Effects on traveling of bridge users.

(2) Effects on local industry's productive capacity.

Effects on traveling of bridge users can be summarized as the consequences of lacking accessibility. Both residents and businesses that are located around disaster-affected regions have to face problems of traveling. Vehicles in this traffic-affected area have to detour during bridge closure period. When alternative roads do not provide similar and sufficient accessibility as the damaged bridge, both residents and business will have to travel extra distance and waste more time on traffic. In some extreme conditions, bridge closures can alter transportation methods entirely. After the Vanuatu earthquake in 2002, transportation of supplies mainly relied on the wharf because a bridge was damaged and could not be used for transportation for some time. The extra detour costs could include transportation costs and increased operating expenses of the wharf (McKenzie, Prasad & Kaloumaira 2005). The additional vehicle operating costs of extra travel distances and opportunity costs of extra travel time would incur to all bridge users, including local residents and local businesses (Negi et al. 2013). In this part, distance and time saving could be indicators to estimate extra expenditures for bridge users.

Regarding local businesses, transportation disruptions can impact their production capacity. In some areas, bridges are essential to local economic activities. For example, the replacement value of the San Francisco Oakland Bay Bridge has no reason to be equal to the loss in activity caused by the bridge closure. The output value of the bridge would be mainly concerned for the impacts to local businesses (Hallegatte & Przyluski 2010). In road networks, a bridge can act as a time-saving and convenient path for transportation. For traditional industries, transportation and accessibility mean workers, raw materials, and products delivery. Transportation connects and provides the production factors that guarantee the production capacity of the local businesses. The damaged bridge can cut off or decrease connection of different road networks and social aspects. Without sufficient production condition and arrangement, local businesses and industries will suffer losses of decreasing productivity (Hallegatte 2008). In addition, access makes immediate response possible to local farms and companies. The immediate responses include: getting farm products to market, replacing damaged equipment for farms and local businesses, and going back to working positions. A bridge could stop help from one side to the other sides.

Also, associated facilities, such as power, sewer, water, the internet, workers, etc.(Dalziell & Nicholson 2001) would rely on the bridge. Bridges play an important role in the rehabilitation of associated road infrastructures (Dalziell & Nicholson 2001). In Lockyer Valley, power was damaged in 2013 flood events and communication was cut off in 2011 flood events. As one of the critical paths to some farms and businesses, the bridge would impact recovery of power and communication. Both power and communication are important to resuming businesses and further restoration.

To sum up impacts on local business, each type of resource that the bridge could provide to local business would be treated as an input to local business. When the supplying of this resource cannot meet the requirement of local business, it is believed the productive capacity of local business is affected by bridge damage.

3. Losses due to historical buildings and psychological impacts on bridge users

In terms of direct intangible costs, there are mainly damages and losses that could not be measured by market value:

(1) Historical bridges will have special intangible values -for example, the value of history, the value of memory, value of arts, special design, etc (Ahmad 2006). These historical buildings are cherished and expected to keep original appearance. Therefore, lots of money has been invested, and different methods have been applied to protect historic buildings in each year (Fu-lan 2008; Le Metayer-Levrel et al. 1999). The heritage values of historical buildings are intangible and cannot be easily estimated by market value. Any irreparable damage will create intangible impacts on heritage value. These historic buildings cannot be easily replaced or demolished. Intangible values will lose when historical building are demolished or destroyed. It is important to concern intangible value to the public when historical buildings are damaged.

(2) There may be psychological distress impacts on individuals whose daily trip will be affected by the damaged bridge. There would be different behavior and response to bridge collapse. From previous research, 90 percent of traveller would not cancel their daily trips. Residents would change their departure time, alternative road, and travel mode after bridge closure. The majority of Travellers stated that they departed earlier than usual on the day after bridge collapse (Zhu et al. 2010). There is obvious inconvinience to bridge users with less flexibility in their schedule. This research would concern psychological impacts on bridge users when they realized that their daily trips and travels would be impacted. Traffic problems will lead to different psychological problems including stress, anxiety and other

emotional changes. During bridge damage, this research propose to concern two aspects of psychological impacts:

The first aspect concerns psychological impacts on the bridge users. When the bridge users cannot travel via bridges, how they react and the negative impacts on their emotions and feelings. Bridge users would realize that their trips, travel, daily plan, etc., would be impacted during bridge recovery. Longer detour distances, extra travel time costs, and terrible road condition will impact traveller's emotions and behaviours (Evans & Carrère 1991).

The second aspect should consider reaction from the local council to minimize the psychological impacts or emotion changes of bridge users. In the Lockyer Valley region, the local council set a temporary bridge to help local community to provide a temporaty route to bridge users (Figure 4.5). Bridge users' reactions to the supports that are provided by the local council worth to be considered. For the local council, it is important to know the effectiveness of supports, and how to optimize resources to minimize the negative psychological impacts on bridge users.

Installation of abutments and the visible detour at Kirsop Bridge, Murphy's Creek

Figure 4.3 Temporary bridge for bridge users (Queensland Reconstruction Authority 2015)

4. Losses of trusts in authority, Losses of unemployment, Environment losses

The indirect intangible costs are mainly related to social impacts on a bridge-damaged affected region:

(1) There will be both positive and negative change in local labor markets (Enke, Tirasirichai & Luna 2008). It is evident that bridge recovery and construction will provide job opportunities to local construction markets. In Lockyer Valley, an interview that was conducted by CRC showed that the construction and quarry industries increased their businesses after flood events. Apparently, bridge recovery made contributions to employing construction works and purchasing a certain amount of rocks. Other companies, such as inspection, consulting and designing companies were also involved in bridge recovery. However, some other researchers pointed out that total employment will decrease after flood

events (Enke, Tirasirichai & Luna 2008; Sarmiento 2007). Accessibility and traveling are considered as one of the reasons for unemployment (Enke, Tirasirichai & Luna 2008). As a significant connection between two sides of the river, loss of accessibility to their workplace would lead to some workers lose their jobs temporarily or permanently. In theLockyer Valley region, some pickers complained they lost jobs for a while after a flood event because they could not reach the farm. Some workers could not reach their work and lost their job temporarily. As local inhabitants mentioned "access is their livelihood." For local employment and labor markets, bridge damage would lead to two types contrary impacts on the local community. On one hand, damaged bridges bring more recovery- related job opportunities to the local community that would benefit local labour market after flood events. On the other hand, bridge damage causes unemployment due to traveling and accessibility difficulties. Lots of cases agree that the trend of employment rate is descendant after flood events (Enke, Tirasirichai & Luna 2008). There are explanations for this trend. Construction and related industries need qualified and proficient workers. That is also why workforce shortages in construction sectors are common in disasters reports (Chang, Y et al. 2011; Green, Bates & Smyth 2007; Stevenson et al. 2014). Only a small particular group of residents with qualified skills can benefit from these industries. Also, construction sectors recruit workers from outside of the disaster-affected region. Some residents are not able to get construction- and recovery-related jobs when they lose their jobs after a flood event. Currently, more detailed surveys and interviews are required to determine what role a bridge plays in unemployment change.

(2) The local council may suffer a crisis of loss of authority. This is a new phenomenon that can be found in the Lockyer Valley interview. According to the research conducted by CRC Australia, some of the residents showed a lack of trust and confidence in the decisions of the local council. Some of their complaints were(Jane Mullett 2015):

(a) They could not be involved and participate in the recovery process. Some people complained about the consultation meeting. The local council just showed the existing plan instead of listening to and accepting their opinions. This seemed to be a problem of information transparency and communication between the local council and the residents. Residents expected more feedback from the local council. However, the local council could meet the expectation of the local communities and could not provide enough interaction opportunity to the local community.

(b) Local inhabitants were not satisfied with receptions and response from the local council. Some residents complained the there is nowhere to get help. Others said that the local council set up an office to help them deal with their access issue. However, these people complained the office did not provide meaningful help due to their rigid criteria. In this case, setting up an office to deal with access problems of inhabitants should be a good idea. However, the local council should inform residents and provide more help to the local inhabitants.

(c) There is also a problem of fairness. The repair order could impact traveling of people who settled down in different regions. After the 2011 flood event, some people accepted help from the local council while others were not. Though they were all appreciative of the efforts that are made by the local council, the local council still needed to improve their work to take care all residents well.

Results indicated that authorities and trust of local council would be challenged. It also showed that establishing a good solid relationship between residents and the local council was difficult during a bridge recovery period. The local council would concern how to improve their performance to give confidence to local inhabitants. In this case, the local council had already made efforts and investments to improve consultation, participation, and providing help. However, local inhabitants were not satisfied with the local council. The economic losses could be in proportion to the efforts and investment of the local council. Therefore, information about reactions and degree of satisfaction from residents needs to be collected.

(3) Last but not least, waste and debris disposal have indirect intangible impacts on the surrounding environment (BDA Group 2009; FEMA 2007). These impacts include gas

emissions, greenhouse effects, and leachate and amenity impacts. They can be measured by the expenditures that are made to minimize these effects. In Australia, government reports provide an index to measure the cost of the economic impacts of debris and construction waste.

4.1.2 Causes and effects analysis

Different types of economic impacts are summarized into different classifications. To illustrate this classification is reasonable, this research would use figure 4.6 to show the cause and effect of different economic impacts of bridge damage.

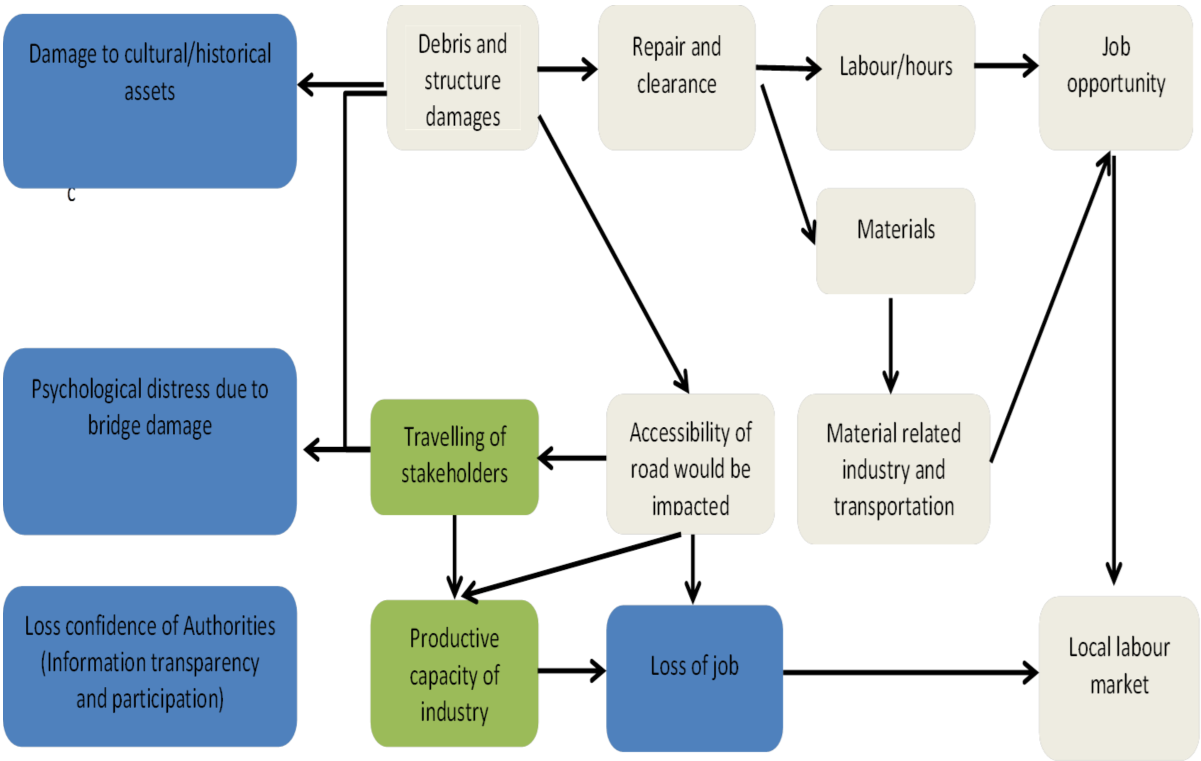


Figure 4.4 Cause and Effect Analysis

During flood events, structural components of a bridge may be damaged. In addition, flood events can bring debris from the upstream side. Both direct damages on the bridge body and debris that builds up around the bridge affect the accessibility of the bridge.

For direct loss in this research, direct impacts are related to the bridge directly. First of all, repair and cleaning work used to get the bridge recovered would be directly applied to the bridge. Some historical buildings have intangible value to the public. The extra value should be considered for this bridge. Additionally, bridge damage could create psychological impacts on stakeholders of the bridge including unhappiness with bridge damage, the anxiety of traveling, unhappiness to detour, etc. These impacts are caused by bridge damage directly. Therefore, all these impacts are direct tangible costs.

During bridge recovery, the bridge could be closed or only partly open to the public. Bridge accessibility cannot be guaranteed, and traffic conditions become terrible. Therefore, accessibility can create different economic impacts. First of all, traveling of stakeholders would be affected. Their travel plans and the daily trips would change due to the post-disaster condition of the bridge. There would be increasing travel costs for the detour. Stakeholders would also suffer opportunity costs from the increasing travel time. For the local industries, traveling of stakeholders can impact productive capacity by cutting off their production material supplies. These impacts are caused by the change of bridge accessibility. Therefore, they considered as indirect losses.

For labour market change, there are two trends during bridge recovery. First of all, debris cleaning and bridge repair would provide construction and related job opportunities. However, negative traffic impacts on stakeholders and local industries would have negative impacts on employments. There is obviously an increasing unemployment rate in flood-affected regions.

Another indirect impact is loss trusts on local authorities. This type of impact is caused by information transparency, communication, participation and support problems that happen during bridge recovery. There are complex reasons for residents to feel displeased with bridge recovery. Trust loss is another secondary impact that is caused by bridge recovery.

In this research, tangible and intangible are introduced to distinguish economic impacts by whether these economic impacts can be measured by the monetary flow. For losses that can be valued by price or market value, these losses would be considered as tangible losses. For losses that have no market prices and could not be measured by monetary value, losses are considered as intangible.

4.1.3 Categorize different classification of economic impacts of bridge damage in flood events.

In this graph, different economic impacts which are mentioned in different types of studies are summarized and combined (Figure 4.7):

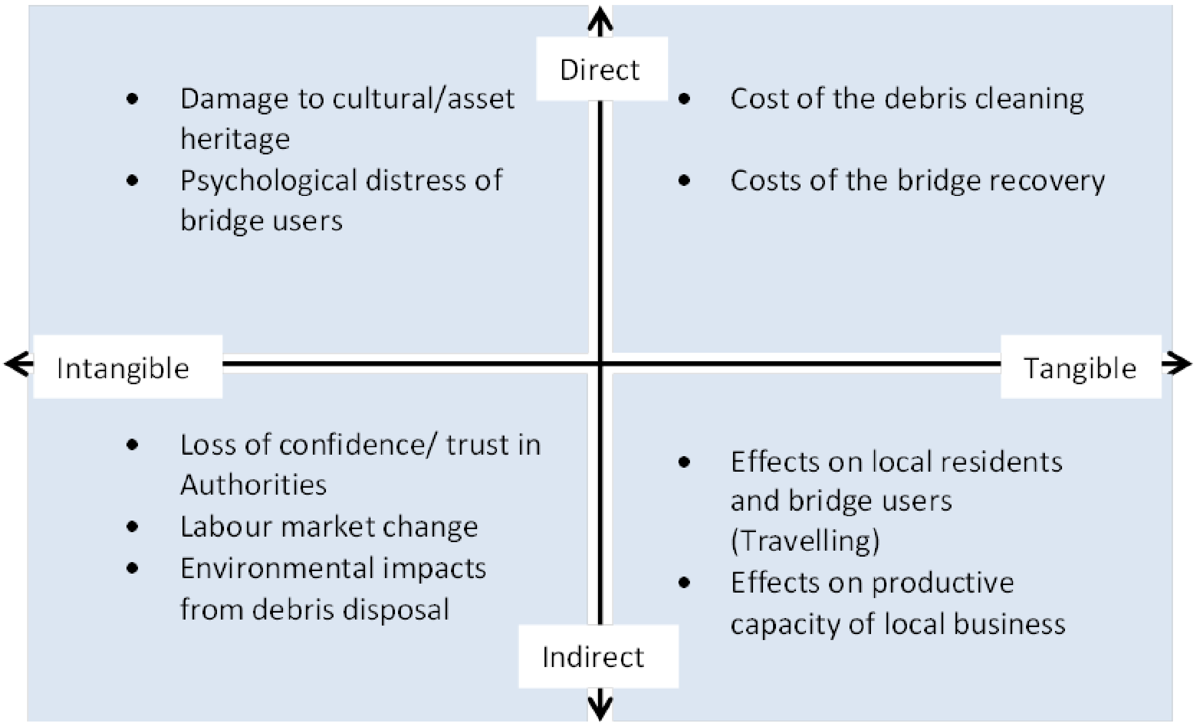


Figure 4.5 Economic impacts of bridge damage

The classification of economic impacts is based on two concepts. The direct losses and the indirect losses are based on the order of consequences to the bridge damage in flood events. The tangible losses and intangible losses are distinguished by monetary flow and market price.

Figure 4.6 points out a continuity of the consequences to the occurrence of the bridge damage in a flood event. Direct losses are the first-order consequence due to bridge damage. The indirect losses are derived from the second- and third-order consequences.

Market value is a critical concept to distinguish the tangible and intangible. The tangible cost can be interpreted as objects with a market value or resource flows which can be easily specified in monetary terms. For intangible losses, they either have non-market value or are difficult to give a monetary value. In this research, prices that cannot be accepted by all the public are also considered intangible losses- for example the will-to-pay cost of historical bridge damage and the environmental damage that is caused by debris disposal. Here are some explanations for each economic impacts.

The cost for debris cleaning refers to the costs of the whole procedure of debris cleaning, including debris collection, debris transportation, and debris disposal. Also, debris includes the construction waste that is created during bridge recovery.

Costs of bridge recovery include costs of repairing/replacing damaged bridge structures. In some cases, there is improvement on bridge after bridge recovery. For example, a steel bracing plan was included in the Kapernicks bridge repairs after the 2011 flood. All these expenditures would be included as costs of bridge recovery.

The effects on local inhabitants and bridge users (Traveling) consider the cost of bridge users' detours. This would include money spent on extra traveling distance and the opportunity costs of extra traveling time.

Effects on the productive capacity of local businesses refer to the losses due to business interruption and decreasing productive capacity caused by bridge damage. There are mainly three types of impacts of bridge damage. (1) The ability to transport production material via the bridge before and after a disasters impacts production. (2) The availability of associated facilities that are accessed via the bridge, for example, power, water and the internet, is affected. (3) Access can impact the resumption of business. For example, it can impede industries and farms in getting equipment and machinery to resume business and accelerate further rehabilitation.

The value of cultural/heritage asset means the bridge or bridge components has a heritage value. Historical buildings will have special intangible values, for example, the value of history, the value of memory, value of arts, special design, and so on (Ahmad 2006).

Psychological distress of bridge users refers to the distress, pressure, and other emotional changes when they realize the bridge is damaged and the damage will impact their daily trips. With 90% bridge users would not cancel their travel plan (Zhu et al. 2010), the emotional reactions of these residents need to be concerned

Loss of trust/confidence in authorities means local residents would be not satisfied with the plans, reactions, and support of the local government during the bridge damage period.

Labor market change means changes of employment due to bridge damage. There are two opposite impacts: Bridge recovery brings job opportunities to the local market; however, there are also people who would lose their jobs temporarily or permanently due to access problems.

Environmental impacts from debris disposal mean the impacts of gas emissions, greenhouse effects, leachate, and amenity impacts from debris disposal. Standards of Australian government are applied to measure each type of impacts.

In this matrix, some of these economic impacts can be measured by current knowledge: the costs of debris cleaning, costs for bridge recovery, effects on residents and bridge users, effects on business transportation, and effects on air emissions to the environment. Although there are approaches that can be used to estimate costs on these aspects, the accuracy of these methods needs to be improved.

For historical buildings, The Australian government has already prepared to measure the heritage value of buildings that is based on the willing-to-pay method. The result of the willing-to-pay method is based on surveys and interviews. Therefore, the result of willing-to-pay is various and not accepted by all individuals.

Some of these impacts cannot be accurately estimated by current knowledge. Currently, loss of confidence/ trust in authorities and labour market change cannot be accurately predicted after flood events. Only changes on these two aspects can be observed. However, there is still a lack of evidence and data to validate these impacts.

For the psychological impacts on bridge users, it is discussed by the best judgement of researchers. More research data need to be collected to conduct further research.

CHAPTER5 INTEGRATED MODELS TO ESTIMATE ECONOMIC IMPACTS OF BRIDGE DAMAGE IN FLOOD EVENTS

5.1 Introduction

This chapter will introduce different models to estimate economic impacts that are caused by natural disasters. That will involve multiple existing models to measure each type of economic impact. Estimations will be concluded and seperated into different aspects and sectors due to methods of estimation:

(1) The first part will estimate expenditures on bridge recovery. It will include debris clearance and bridge recovery. After flood events, the post-disaster inspection will be recommended by the local council. It is a necessary and useful way to guarantee the strength and safety of the bridge. Reports of inspection are also important data sources for estimating bridge recovery costs. However, there will be two shortages of inspection reports. In different inspection reports, there will be different rules and descriptions for bridge damage. Otherwise, methods that are used for inspection reports may not be suitable for estimating the repair costs of bridge damage. In this part, the damage performance group and the damage state methods are introduced to help estimate the repair costs of damaged bridges' structural components. Performance groups would break the whole bridge into different performance groups. Performance groups would consider structures that transfer same stress and can be repaired together. That avoids double accounting of repair costs. The damage states methods would provide consolidated and accepted damage concepts to measure repair costs of damaged bridge structure components.

In debris collection, debris disposal would concern disposing debris without harm to surrounding environment. According to the Australian government report, there are different disposal methods between different debris and construction wastes. Despite the debris types, the disposal would concern location and size of disposal and dump sites to calculate the expenditures on disposing of debris properly. A cost index, which is based on 2010 price level, would be introduced.

(2) The second part would calculate the extra costs of bridge users. It will discuss costs of extra traveling distance and extra traveling time. In this part, vehicle operating costs for each type of vehicle on the road would be important. The extra traveling costs vary from vehicle types and vehicle purchase prices. A model would be introduced to help measure regional vehicle operating costs due to local vehicle constitution and distinguishing features.

In addition to the local vehicle operating costs, a detour route is also an important factor that would impact traveling distance and travel time. In this part, it is important to identify alternative routes after bridge closure. The choice of the alternative road depends on post-disaster conditions of the road, convenience, and guides of the local council. Therefore, a regional road network is needed to help estimate post-disaster traffic and transportation conditions.

In this chapter, the first step is to introduce performance groups, vehicle operating costs, debris disposal costs, and GIS maps. The estimation of economic impacts will rely on results from these important concepts and models.

This model has a limit. The performance groups and damage states are only used for concrete bridge while other models in this chapter can be applied to different types of damaged bridge. Debris disposal, costs of detour, impacts on business, historical bridge, losses of authorities are not limited to concrete bridge only. Other models are recommended to measure related economic losses that are related to bridge damage.

5.2 The performance group and bridge damage states of concrete bridge

After bridge damage is recognised, the first step in estimating the economic impacts of the damaged bridge is to collect bridge damage information. The accuracy and degree of detail of the bridge damage information will influence the accuracy of the estimation. A detailed and accureate description method is necessary at this stage. In this research, a method that is used to evaluate concrete bridge damage condition would be introduced.

Performance group and damage states methods are introduced at the beginning to measure damage in seismic disasters. At the present stage, studies have most comprehensive knowledge on seismic disasters. FEMA develops potential models to help estimate and record concrete bridge damage after an earthquake. Damage to main bridge structure components are associated with factors, for example, drift ratio, deck strain, and plastics (Berry & Eberhard 2004; Goel & Chopra 1997). For each type of bridge structure component, there are standards for factors that distinguish each damage state. This method is also accepted for research on bridge damage in other types of natural disasters. In Padgett et al.’s 2008 research (Padgett et al. 2008; West & Lenze 1994), these methods of stating damage are used to describe bridge components’ damage in hurricane events. A hurricane is the disaster that combines both floods and wind impact on the bridge. This research would also use this method to help differentiate damages on each bridge structure component.

There is a limitation of damage state and performance groups. In this part, only concrete bridges are discussed due to current knowledge gap. Timber and steel structure bridge should be discussed separatedly.

5.2.1 Structure performance group

In flood events, different structure elements of the bridge could be damaged and destroyed due to the constant impact and stress of scouring from flood torrents. According to summary of 383 bridge failure cases, 14.9 percent reported damages to the superstructure, 24.5 percent to the pier, and 71.8 percent to the abutment; in 43.2 percent of the cases, the damage extended to the approach roads (Chang, FF 1973). This survey of 383 bridges, which are damaged in flood events, illustrates that all bridge structure components can be damaged and destroyed in flood events.

When damaged bridge structure is inspected and repaired, there are problems to state bridge structure damage conditions and repair procedure. First of all, a whole bridge can be broken into many small detailed structures or different main structures. For example, an abutment is comprised of shear keys and back walls. During the repair procedure, some structures will share the same repair items. For example, both the back wall and abutment reinforcement need excavation on the back wall. Repeated preparations will lead to hard-to-handle repair decisions and double counting the repair costs.

Therefore, distinguish between identical structures, structures in different positions should be numbered. Secondly, in a bridge, different structures will influence the strength and safety of connected structures. In this case, performance groups are introduced to help.

A performance group means that the whole bridge will be broken down into structure groups for each major bridge structure. Performance groups can be considered as major bridge components in which many substructures work together to transfer loads and need to be repaired together (Mackie, Kevin R, Wong & Stojadinovic 2011; Mackie, Kevin R, Wong & Stojadinović 2010). For example, the abutment may consist of shear keys, back walls, bearings, and approach slab. There are three advantages of setting performance groups:

(1) Performance can be treated as a unit and allows meaningful assessment (Mackie, Kevin Rory, Wong & Stojadinovic 2008)

(2) Estimation can avoid double counts of repair costs of different structures' components (Porter 2003).

(3) Decision and estimations can be conducted independently for each performance group.

For a concrete bridge, performance groups can be distinguished from eight aspects as listed below (Mackie, Kevin Rory, Wong & Stojadinovic 2008):

(1) Columns- one performance group per column

(2) Deck/Superstructure- one performance group per bridge span

(3) Abutment- one performance group per abutment

(4) Bearings- one performance group per abutment including all bearings

(5) Shear keys- one performance group per abutment including both external shear keys

(6) Approach- one Performance group per approach

(7) Abutment piles- one performance group per abutment

(8) Pile groups- one performance group per column

Compared with performance groups that are used for earthquakes, this performance group does not separate columns into two groups due to maximum displacement and residual displacement, which are critical seismic-related parameters that are mainly caused by inertial loads. In this research, column damages are only related to their broken condition, not their drift ratio.

Identification will be used in this research to distinguish each performance group clearly. Each performance group will have its identification to show its location and distinguish it from other performance groups. The location is a short text that could be used to identify a performance group's position on this bridge. Here are some principles to help observers set performance groups:

(1) It is better to group performance groups with same characteristics such as superstructure performance groups in different positions.

(2) There should be a clear, logical way to number each group. Performance groups' numbers can follow directions from one side to the other side. Also, they can start from damaged parts to sound parts. Performance groups' sequences should help and serve the inspection of damage states

(3) There should be no ignorance of any structure components. All structures of the bridge should be included in a performance group system.

5.2.2 Damage state of performance group

The loss assessment requires having properly defined bridge damage states for different structures (Mackie, Kevin R, Wong & Stojadinovic 2011). FEMA has a comprehensive and clear five-damage-state method for different structures due to their impacts on bridge stability and reliability. The first level of these damage states is that the structure component is not damaged. However, recording the undamaged components are meaningless during the inspection. Therefore, damage states begin from slight damage in this thesis. Different damage states (NIBS 2003) and related repair solutions after flood events can be presented as below:

(1) Columns

The damage of columns can be described by four circumstances:

(a) Slight, damage state 1(Ds1), is concrete cracking;

(b) Moderate, Ds2, is the onset of cover concrete spalling;

(c) Extensive, Ds3 is the buckling of reinforcing bars;

(d) Complete, Ds4, is the column failure.

(2) Deck and Superstructure

Damage on superstructure and bearings can be summarized:

(a) Slight, Ds1, minor cracking to the deck;

(b) moderate, Ds2, any connection having cracked shear keys or bent bolts, keeper bar failure without unseating rocker bearing failure;

(c) Extensive, Ds3, any breakage, collapse;

(d) Complete, Ds4, Deck washed away, collapse or tilting of the superstructure.

(3) Foundations

Foundations include column foundations and abutment foundations. Column foundations are comprised with piles and pile caps, while abutment foundations consist of piles, pile caps and attached wing walls.

There are only two damage states for the pile foundations and pile caps, including the condition with no damage after disasters. The only interpretation for damage state is minor ground settlement resulting in few piles (for piers/seawalls) getting broken and damaged. In this research of bridge collapse in flood events, there are not only the ground settlement but also the impacts from debris which brought by torrent. Therefore, the Ds1 could be the ground settlement, impacts resulting in few piles (for piers/seawalls) getting broken and damaged.

(4) Abutment

Four damage grades of the abutment can be described as:

(a) Slight, Ds1, is defined by minor cracking and spalling to the abutment, cracks in shear keys at abutments;

(b) Moderate, Ds2, moderate movement of the abutment (<2"), extensive cracking and spalling of shear keys, any connection having cracked shear keys or bent bolts;

(c) Extensive, Ds3, vertical/lateral offset of the abutment, differential settlement at connections, shear key failure at abutments;

(d) Complete, Ds4, any connections losing all bearing support may lead to imminent deck collapse or tilting of the bridge.

(5) Approach Road

The bridge approach represents the roadway which is connected the beginning and end of the bridge. Floods can wash away the road and erode the roadbed or even degrade the river bank. Damage grades on the road can be interpreted as below:

(a) Slightly, Dg1, is surface cracks or onsets pavements problems;

(b) Moderate, Dg2, extensive cracks, settlement of the approach;

(c) Extensive, Dg3, major settlement approach, breakage, partly collapse;

(d) Complete, Dg4, road and its roadbed are severely collapsed, washed away.

Appendix.1 will provide the possible repair solution to different damage states of different structures and how to calculate quantities of repair materials.

An accurate post-disaster damage states would be useful for predicting the time limits of recovery projects. It is important to evaluate the time from bridge damaged to bridge get recovery. The local council would consider the time of found application, designing, construction contract and order sequence of recovery.

5.3 Regional vehicle operating costs

Vehicle operating costs will be correlated mainly to two types of costs: (1) debris transportation (2) detour of bridge users.

Debris transportation is an inevitable part of debris clearance costs. The average vehicle operating cost of the heavy truck and the average delivery distance to dump sites will determine the expense on debris cleaning.

The detour of bridge users would consider the costs of the extra traveling distance and the extra traveling time when the bridge is closed. Measuring detour costs can be challenging. First of all, the constitution of vehicles will impact results a lot. There are variations of vehicles on the road. They have different engine sizes, body weights, engineer types, fuel types and so on. The average operating costs would be different for different types of vehicles. Before estiamtion, they need to be classified due to their fuel type, engine size, and body weight. Second, detour routines are not fixed. There are multiple daily destinations and different alternative roads that could connect to these destinations. Distributions of bridge users on the alternative road are necessary. The other concern of alternative roads is that increasing traffic on an alternative road will improve traffic load and cause unexpected traffic congestions and problems. That will also increase transportation cost.

In this thesis, a model that can classify vehicle types and use regional traffic data will be introduced. Vehicle operating costs will take the average traveling speed and road surface condition into consideration. This model will suit the area that has multiple types of roads with speed limits and vehicles traveling at low speeds. This model allows the use of regional data as parameters to calculate vehicle operating costs that are close to the regional level.

5.3.1 Estimate regional vehicle operating costs

Vehicle operating costs include owning, operating and maintaining a vehicle. It is combined with fuel consumption, tire wear, maintenance and repair, oil consumption, capital depreciation, license and insurance, and operator labour and wages. Operating costs will vary a lot from different vehicle conditions such as vehicle weight, vehicle frontal area, engine coefficient, vehicle costs, etc. Therefore, vehicles need to be separated into different groups to estimate the operating expenses of each type of vehicles. Vehicle groups should take total traffic numbers, automotive specifications, and automotive numbers into consideration. Vehicles can be categorized into small sedan, medium sedan, large sedan, SUV, pickup and full-size SUV, light commercial, light truck, rigid truck, heavy truck, etc. A larger number of classification groups can provide more accurate results for different types of vehicles. However, having more groups would increasing the difficulty of estimation. More vehicle specification and related parameters need to be collected.

Equations and steps of vehicle operating costs are shown below (Berthelot, CF et al. 1996):

(1) The fuel consumption cost

The fuel consumption costs of vehicles are mainly related to total resistive forces, mechanical efficiency, and fuel energy content. The fuel consumption cost can be calculated as below:

$$\mathrm{Fuel} = \mathrm{R_{total}}/[\mathrm{l_{total}}(\mathrm{E_{cf}})] \tag{1}$$

Where, fuel= fuel consumption rate (L/m), $\mathrm{l_{total}}$ = total mechanical efficiency, $\mathrm{E_{cf}}$ =fuel energy content (KJ/L), and $\mathrm{R_{total}}$= total vehicle resistive force (N).

$$\mathrm{l_{total}}=\mathrm{K_{engine}}\mathrm{K_{trans}}\mathrm{K_{diff}} \tag{2}$$

$\mathrm{K_{engine}}$ = coefficient of engine efficiency, $\mathrm{K_{trans}}$ = transmission efficiency, and $\mathrm{K_{diff}}$ = coefficient of differential efficiency.

$$\mathrm{R_{total}} = \mathrm{R_{roll}} + \mathrm{R_{drag}} \tag{3}$$

Where, $\mathrm{R_{roll}}$=the rolling resistance (N), and $\mathrm{R_{drag}}$=aerodynamic drag.

$$\mathrm{R_{roll}} = \mathrm{C_r}\mathrm{W_{vehicle}}\mathrm{k_r}\mathrm{K_s} \tag{4}$$

Where, $\mathrm{R_{roll}}$ = the rolling resistance (N), $\mathrm{C_r}$= coefficient of rolling resistance, $\mathrm{W_{vehicle}}$=gross vehicle weight (N), $\mathrm{k_r}$= coefficient of road roughness, and $\mathrm{K_s}$=coefficient of road stiffness.

$$\mathrm{R_{drag}} = 0.5\mathrm{r}\mathrm{C_d}\mathrm{A}\mathrm{V}^2 \tag{5}$$

Where $\mathrm{R_{drag}}$=aerodynamic drag; r= air density (kg/m^3), $\mathrm{C_d}$= wind mean averaged coefficient of drag, A= frontal area of vehicle (m^2), and V= velocity of vehicle (m/s)

At this stage, most parameters introduced in these equations are constant quantities. The mechanical efficiency, fuel energy content, the coefficient of road roughness, the coefficient of road stiffness, and the wind mean averaged coefficient of drag would not change a lot in one region. The air density also has an average value in a certain latitude and season.

Variables that will eventually affect fuel consumptions are the average weight of vehicles, frontal area of vehicles, and velocity of vehicles. These three factors illustrate that there will be obvious differences between heavy trucks, SUVs and Sedans, which is attributed to their various designs and their weights. Moreover, it is important to monitor the average speed of each type of vehicle via the bridge. Therefore, at the first stage of estimation, the average fuel consumption of each type of vehicle used to travel via a damaged bridge will be estimated separately.

(2) The tire cost

To find the total tire cost, one must measure the average cost of tire abrasion in the extra distance travelled during the period when the bridge is damaged. The road surface texture and roughness will determine effects on the tire cost. The tire cost for a vehicle can be expressed as:

$$\mathrm{TC} = \frac{\mathrm{C_t N_t}}{\mathrm{L_t k_{tt} k_{tr}}} \quad (6)$$

Where TC= total tire cost (dollar/km), $\mathrm{C_t}$=cost per tire (dollar/tire), $\mathrm{N_t}$= number of tires, $\mathrm{L_t}$= life of tire (km), and $\mathrm{k_{tt}}$=road texture coefficient.

In these formula, average prices and numbers of tires for trucks and light vehicles are different. Therefore, the classification of different vehicles will be sufficient to distinguish vehicles with different numbers and types of tires.

(3) The maintenance and repair cost

In previous researches, the maintenance and repair costs of vehicles could be account up to 30% of vehicle operating costs (Berthelot, C 1992). This result was very close to that of the report released in September 2013 by the Commonwealth in Australia. This report illustrated that maintenance and repairs might count for 32% of the total operating costs. Vehicle maintenance and repairs costs can be expressed as follows:

$$\mathrm{MC} = \mathrm{M_{cf} K_{mr}} \quad (7)$$

Where, MC= maintenance cost (dollar/km), M_{cf}= average maintenance cost (dollars/km), and K_{mr}=road roughness coefficient.

The road roughness coefficient is used to adjust the maintenance cost for different road types. Normally, the maintenance cost on rough road conditions is higher; vehicles that are usually driven on highways are in better condition than vehicles that are driven on less well maintained roads. In this model, road roughness values are set to 0.8, 1.0, and 1.2 to distinguish different performances on a highway, a bitumen or concrete surface road, and a terrible dirt road.

(4) Oil consumption costs

Vehicle oil consumption depends on the maintenance and oil change intervals. The cost of oil is only a small part of vehicle operating cost.

$$\mathrm{OC} = \frac{\mathrm{OCC}}{\mathrm{D_0}} \tag{8}$$

Where, OC= maintenance cost (dollars/km), OCC= oil change cost (dollar/service), $\mathrm{D_0}$= oil change frequency (km/ service).

Normally, the manual recommends that the owner change oil every 3000km to 4000 km. However, the owner often change oil and filter every from 5000km to 10000km.

(5) Capital depreciation costs

The capital depreciation cost of a vehicle is mainly related to the average cost of the vehicle, the average service life of the vehicle, vehicle salvage, and regional discount rates. The capital recovery (CR) cost of a vehicle can be presented as follows:

CR= I (A/P, MARR, Lv) – S (A/F, MARR, Lv) (9)

Where, CR= capital recovery (dollars/year), I = Initial capital cost (dollars), S= salvage value (dollars), i = discount rate, and Lv= service life of vehicles.

Average vehicle operating costs are equal to

$$C_{\mathrm{vehicle}} = \mathrm{Fuel} + \mathrm{TC} + \mathrm{MC} + \mathrm{OC} + \mathrm{CR} \tag{10}$$

5.4 Debris disposal costs

Debris disposal could be a big issue after a flood event. Debris disposal will occupy rooms and have impacts on the surrounding environment. For some catastrophes, debris cleaning and disposal will take years. It will be account for a significant part of recovery costs. Debris is extra wastes that are not generated from daily life and unexpected. There are mainly two types of debris around bridges after flood events: putrescible debris and construction waste. In this research, it is assumed that debris disposal will consume extra social resources. In this thesis, expenditures will be estimated as extra resources that are used to eliminate the impacts of debris disposal.

Different types of debris should be disposed by different methods. Putrescible debris is commonly landfilled in all around Australia and most of other countries. Meanwhile, construction wastes are proposed to be recycled due to environmental-friendly concerns and government policy. However, debris disposal methods also concern debris quantities. When there are a little amounts of debris, both putrescible debris and construction wastes can be collected and disposed of together considering the fact that waste division would cost a lot. When there are lots of construction wastes and far more than local recycling processing capacity, the construction wastes will not be recycled properly. Although recycling construction wastes is recommended, there are lots of constraints on the physical truth.

Regarding economic impacts, landfill and recycling are different. During the waste recycle procedure, the costs are simply processor gate fees. It nearly has no impacts on the surrounding environment and effectively decreases the consumption of construction materials. Compared with recycling construction, the landfill will have long-term and negative impact on the surrounding environments. To recover the accessibility of bridges, the debris around bridges should be cleaned.

5.4.1 Recycling construction waste

According to a government report, more than 50% of construction and demolition wastes were recycled or reused in 2003 (Commonwealth of Australia 2006). The Australian government encouraged construction waste to be recycled and to improve waste recycle percentage as much as possible. The recycling targets for different states are averaged 80% (Hyder Consulting Pty Ltd 2011). On this circumstance, construction wastes should be recycled if recycling conditions are available.

Table 5.1 The recycling rate of construction waste in 2003

State Territory	Recycled Construction and Demolition Wastes
New South Wales	71%
Victoria	54%
Queensland	42%
Western Australia	21%
South Australia	67%
Tasmania	NA
ACT	89%
Northern Territory	NA

(Commonwealth of Australia 2006)

Recycling will have fewer negative impacts on the environment. The costs of recycling construction and demolition wastes are mainly a reprocessor gate fee in different states. The recycling of construction and demolition focuses on masonry materials, metals, asphalt, concrete and bricks, timber, soils, sand and fines (Hyder Consulting Pty Ltd 2011). And almost all construction and demolition wastes could be reused. Therefore, for a large amount of building and demolition waste and debris from damaged bridge cleaning and repair progress, recycling is the most economical and environment-friendly method. The total costs for debris recycling at the 2009 price level in different states are as below (Hyder Consulting Pty Ltd 2011):

Table 5.2 The reprocessor gate fee in different states

State	Mixed loads (AUD/ Tonne)
Victoria	50-70
New South Wales	40-80
Australian Capital Territory	104-118
South Australia	30% discount on publicly listed landfill gate fee (42-80)
Tasmania	50
Northern Territory	N/A
Western Australia	45
Queensland	47

In this thesis, the total costs for recycling of construction wastes are costs which are applied in different states. From an environmental aspect, material recycling can save land, decrease gas emissions, and decrease raw materials consumption. In this research, these indirect intangible benefits of recycling are not measured.

5.4.2 Putrescible debris

Putrescible debris will have more indirect tangible and intangible impacts on the surrounding environment. Regarding easing impacts putrescible debris disposal, more social resources will be consumed. The indirect tangible cost during bridge recovery, which is the private cost of waste disposal, is the cost for landfill establishment, operation, and end of life management. The life cycle of each landfill in Australia is 30 years, and the greenhouse emission is usually 50 years from the opening of the landfill. The disposal costs in a well disigned dump site can be summarized as below (BDA Group 2009):

(1) Cost of land purchase

(2) Cost of approval process

(3) Capital cost of equipment and buildings

(4) Cost of lining landfill bases to prevent leaching

(5) Cost of on-site gas recovery and flaring

(6) Cost of fencing and other measures to prevent waste from being blown into adjoining properties

(7) Operational costs including labour, fuel, and materials

(8) Cost of capping landfills and landscaping

(9) Cost of rehabilitation and aftercare

The indirect tangible cost for one-tonne of debris for small, medium, and large landfills at 2009's price level are as below:

Table 5.3 Classification of landfill size

Land size	Category (tonnes/year)
Small	<10,000
Medium	10,000-100,000
Large	>100,000

Table 5.4 Average disposal costs by landfill

Type of cost	Small (AUD/Tonne)	Medium (AUD/Tonne)	Large (AUD/Tonne)
Land	5	3	2
Approvals/site development	10	6	4
Best practice liner	13	8	5
Leachate collection	6	4	3
Gas recovery	6	4	3
Amenity management	1	1	1
Operations	34	20	14
Capping and remediation	10	6	4
Post closure maintenance	15	9	6
Total	100	60	40

Also, debris disposal will aim at minimizing and eliminating intangible adverse effects on the surrounding environment. The negative environmental impacts of debris disposal include the following aspects (BDA Group 2009):

(1) Greenhouse gas emissions, which come mainly from organic waste

(2) Other emissions into the air, such as, SO_X , NOx, VOC, Lead, CO, Dioxins, etc.

(3) Emissions into water (Leachate), these occur when liquid passes through a landfill, where it may have become contaminated, and enters groundwater or sometimes surface waters. A range of pollutants that are found in leachate have the potential to be discharged to groundwater or sometimes surface water.

(4) Amenity impacts -these include the impacts on local communities arising from the operation of the landfill and may cover noise, dust, litter, odour, and pests.

Regarding indirect intangible costs, the toxic pollutants are not considered in this research. The reason is that there are strict regulations of toxic pollutants such that allowable emissions are not generally present in a location, manner and concentration sufficient to cause health and environmental impacts. Moreover, the indirect intangible costs will not include the measurement of the benefits of alternatives to landfill use, such as the potential for reducing virgin material from recycling wastes, garbage power, and garbage compost.

The indirect intangible costs, which are also called "externalities", are tightly related to the environment, human health and social amenities. Two methods are introduced to measure greenhouse gas emission and other types of harmful air emissions. First of all, the impacts of greenhouse gas emissions are measured by the preventative expenditure method, where the price of purchasing greenhouse credits is used as the value of greenhouse gas emissions. Other air emissions, e.g. the PM10 indicator are set as the basis to evaluate air pollution. The explicit system, which has been used in NSW states, is introduced to measure the impacts of different pollutants (BDA Group 2009). Results are shown bellow:

Table 5.5 Emission air value per tonne

Emissions to air	Urban AUD/Tonne	Rural AUD/ Tonne
Benzene	16,000	16,000
Coarse particulates	400	400
Fine particulates	2700	2,700
Hydrogen sulphide	7000	7,000
Mercury	2,400,000	2,400,000
Nitrogen Oxides	1,400	200
Sulfur Oxides	50	50
Volatile Organic Compounds	1,000	140

With regards to leachate, the intangible costs are the health cost and government pollution fees. The costs for leachate are summarized as below (Table 5.6):

Table 5.6 Costs for Leachate

Emissions to water	Urban and Rural AUD/Tonne
Arsenic	54,000
Cadmium	1,447,000
Chromium	,91,000
Copper	37,000
Lead	138,000
Mercury	3,888,000
Total PAHs	82,000
Total phenolics	106,000
Zinc	150

To measure the intangible costs, it is significant to measure average emissions and leachate from one-tonne debris. Gas emission and leachate will vary from different constitutions of debris. According to BDA measurement in Australia, the indirect intangible costs for debris, which are not under proper management can account for 25%-45% of total disposal costs in urban and 20%-40% costs in rural areas (BDA Group 2009). With best practice controls, the cost can be only 4% at the urban area and less than 1% at the rural area. The average intangible costs for best practice control are between 1.5 and 2 AUD/ tonne. For the intangible costs with poor control, the average indirect intangible costs vary from 15-25 AUD/ Tonne. In this thesis, the costs would use the average level that is summarized by BDA:

Table 5.7 Costs for debris disposal

Costs	Good control AUD/tonne	Poor control AUD/tonne
Environmental effects	1.75	20

5.5 Maps of regional road systems

In order to estimate how a damaged bridge impacts the surrounding road network, a regional road network information map needs to be established. For a good regional road network map, it should have a proper land range. This map should be large enough to include a majority of the necessary services and residents in the traffic affected region. The land range is always determined by the location of the bridge, the population and traffic density around the bridge. Land range setting should consider these aspects below:

(1) Residents who will use this bridge in their daily activities.

(2) Local businesses that rely on the bridge as main transportation routine.

(3) Connections to nearest main city and a majority of necessary services.

(4) Distance to alternative roads and bridges.

These four aspects will help to identify the land range of the map and the traffic-affected region. After the land range is set, other information should be added into in this map. A good map should contain enough traffic and route information to support an economic estimation, such as the interflow and communication of the two road networks on the two sides of the river. In order to conduct a map analysis about transportation and traffic flow, the following data are required:

(1) Damaged bridge locations and traffic

(2) Road conditions, types, and traffic conditions.

(3) Main traffic network

(4) Places that can provide necessary services, for example, food, fuel, medical care, education, etc.

(5) Main road and alternative roads to necessary services.

(6) Alternative roads or bridges that are also damaged by the flood events.

(8) Population and business distribution in traffic-affected region.

(9) Basic supply and demand around traffic affected region.

In this thesis, the ArcGIS is recommended to build the road network and conduct a road network analysis. This map allows the use of different layers in classifying different road types and marking the alternative roads, bridges, etc. Also, this map system can provide both road maps and satellite maps. The map works in the following way:

(1) It classifies different road conditions and types. Figure 5.1 is an example and shows the whole view of the main road network around a damaged bridge. First of all, regional roads are basically separated into four types in this map: (a) Highway, (b) the road containing the damaged bridge, (c) the concrete and asphalt surface two-lane roads, and (d) dirt roads. At this stage, a road with different surfaces, widths (lanes), and conditions should be carefully discussed as that information is related to road carrying and transportation capacity.

(2) Locations of the majority of necessary services should be marked in this map. Figure 5.1 shows that the majority of required services are provided by two main cities: Toowoomba and Gatton. The southern bank is only used by farmers and industries. Residents on the southern side of the bridge have to go to these two cities to get fuel, health services, food, etc. The industries and the farms also need to get production materials from the northern bank. However, lots of residents work for the meat industries and farms, which are located on the southern bank. Therefore, this bridge is important for commuters, products, and productive material transportation.

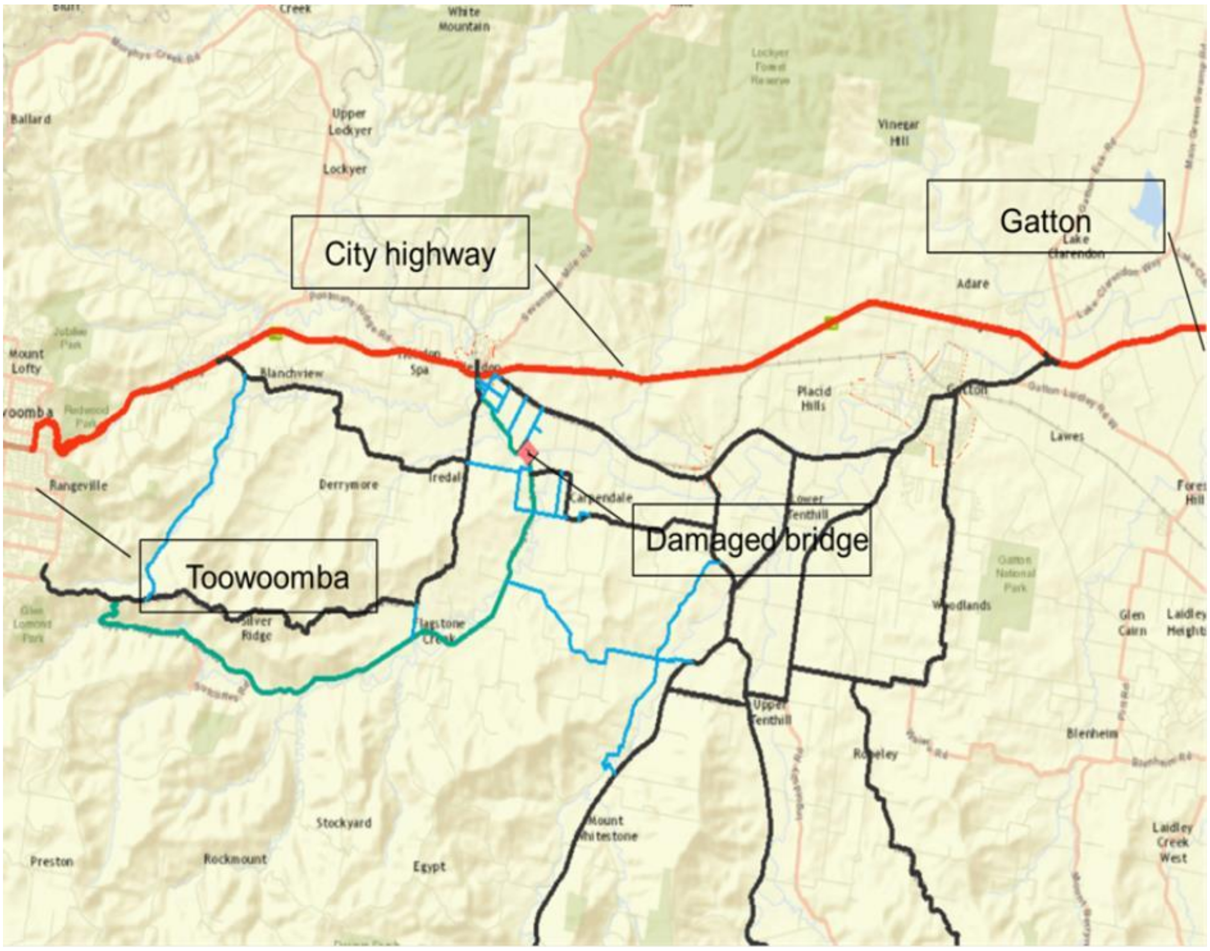


Figure 5.1 Map of the road conditions and classifications

(3) Comparison of different alternative roads after a disaster information. Figure 5.2 shows more details, including two damaged bridges and four damaged sections on the alternative roads after the 2011 flood event. That leads to some alternative roads not be available after the flood events either. In Figure 5.2, yellow lines mark the only functioning alternative roads around the damaged bridge after the 2011 flood event.

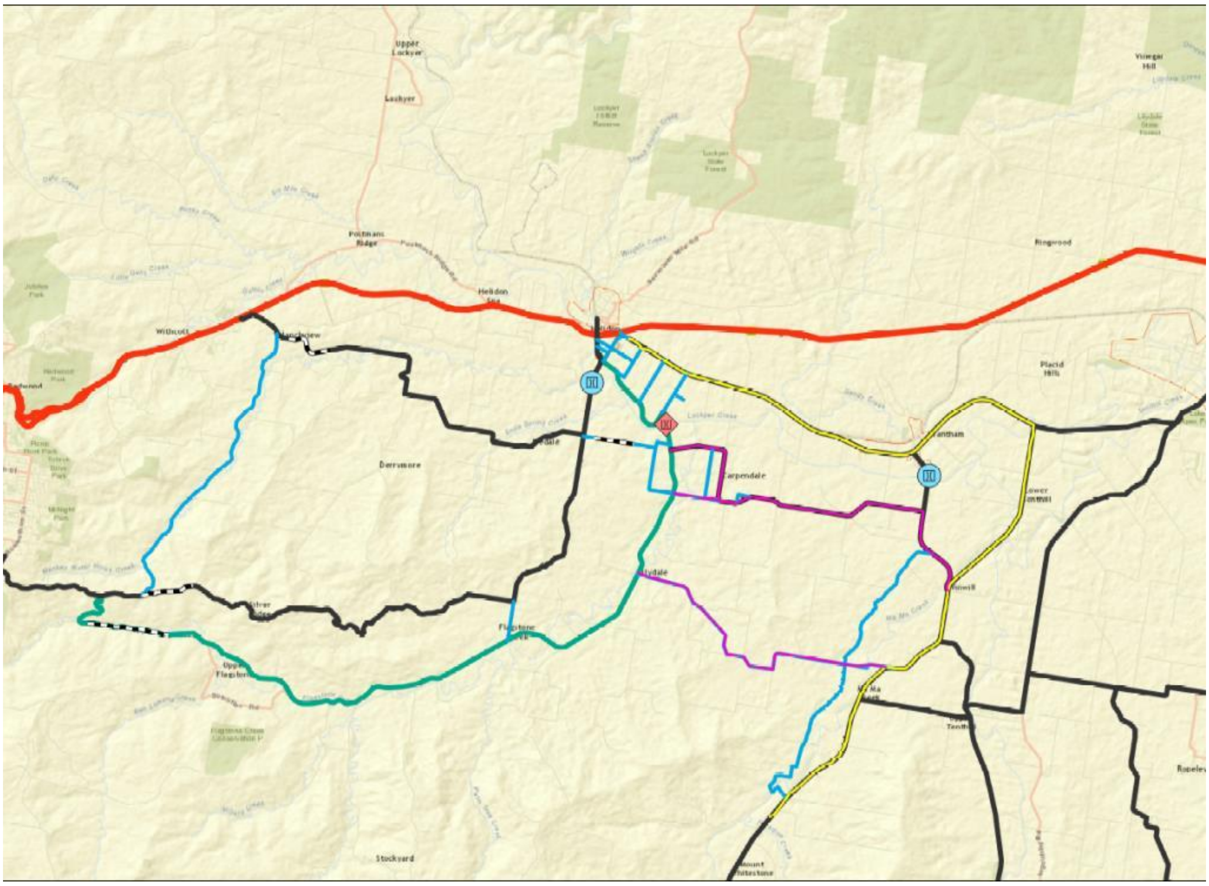


Figure 5.2 The map including alternative roads

(4) When multiple alternative roads exist, traffic distribution information should be added to the map. At this stage, it is hard to collect data on dynamic traffic volume change. Traffic distribution information is generated using road condition, convenience, and distance from the damaged bridge. The method recommended in this thesis measures changes in traffic volume on each alternative road. The value of traffic change can be used to calculate traffic distribution, average traveling distances and traveling times.

(5) In a GIS map, the road map datasets can be transferred into satellite maps. Therefore, all data records can be used with a satellite map. Figure 5.3 shows the land range of the satellite map. Figure 5.4 shows a close view of the map. A satellite map can help analyse the residential and industrial distributions around the damaged bridges. Data and information on population density, the allocation of the residents and industries and topography can be easily obtained from the maps.

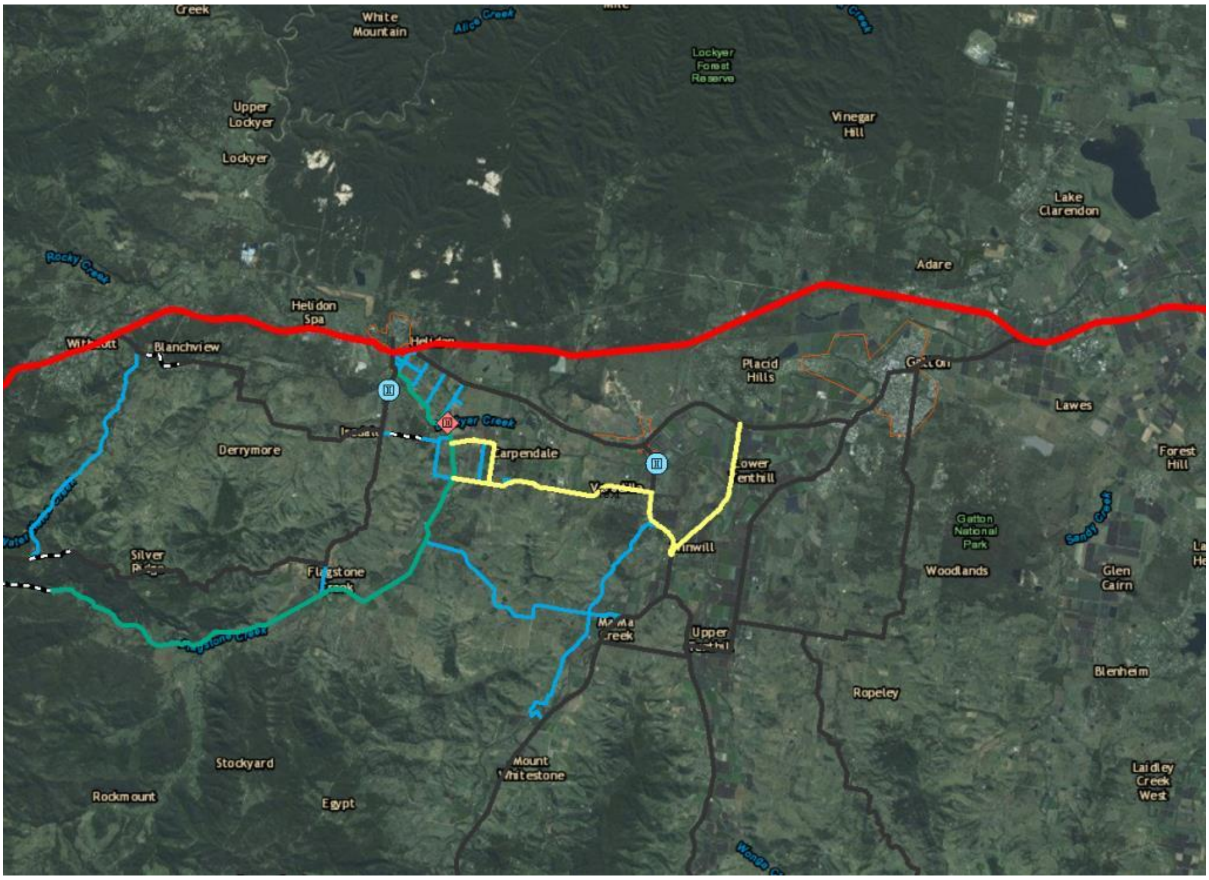


Figure 5.3 The satellite map of the whole land range

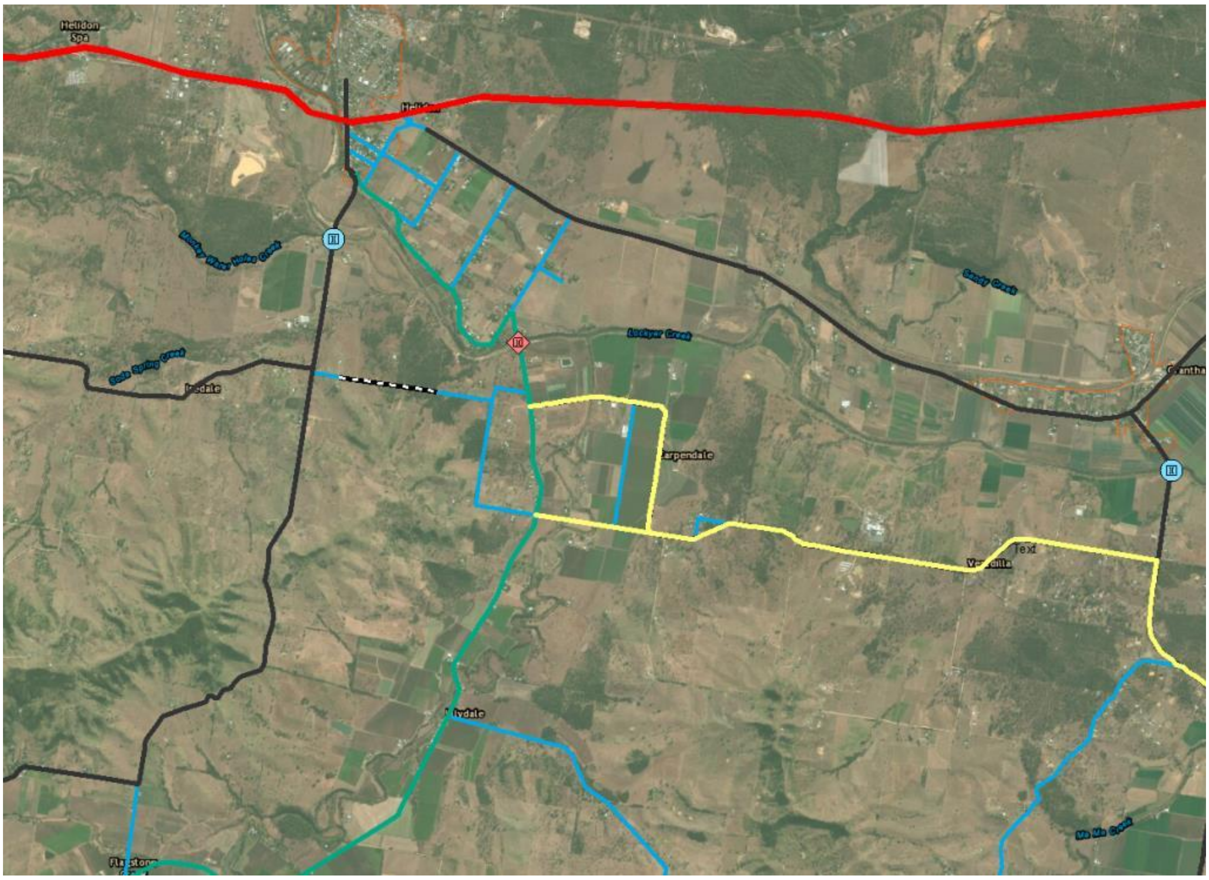


Figure 5.4 Close view of the damaged bridge and the surrounding road networks

(6) At this stage, Google map will be introduced to help confirm traffic affected region, traveling time and traveling distance. Regarding the traffic affected region, it may not be a closed district. To confirm the traffic affected land range, two main parameters, which are additional travel distance and additional travel time, are used. By comparing traveling distance and traveling time that via damaged roads and alternative routes, affected regions can be identified. It is the bidirectional impact on both sides of the damaged bridge. Sometimes, damaged road would hinder traffic flow from different directions or from two particular roads. In some other conditions, an damaged bridge could cut off traffic flow that comes from one road. Normally, the travellers in traffic-affected region will have greater traveling distances and travel times. There would be the marginal point of each alternative road that would have similar travel time and travel distance with the original route. Jointing all marginal points could provide a general view of the traffic-impacted region. There are two steps to calculate the extra travel time and extra travel distance:

In order to compare the difference between travel time and travel distance, the first step is to measure the average travel time and average travel distance via the bridge.

(a) Choose multiple pairs of departure and destination on both sides of the bridge

(b) These routines will include as many directions as possible.

(c) These routines should include main travel destinations and services.

The second step is to measure traveling distances and traveling times that are involved in going via alternative roads:

(a) Use the same departure point and destination in the first step.

(b) Use alternative roads.

(c) Compare each pair of traveling distances and traveling times, and record points with increasing either traveling time or traveling distances.

The results that are derived from Google Maps are the average traveling times with reasonable traffic and road conditions. These results will not consider traffic congestion and road conditions after disasters. With more local information about traffic situations, results can be more accurate. With the additional travel times and distances from each pair of routines, the average traveling distance and time can be estimated.

Figure 5.5 and Figure5.6, as an example, show the differences in traveling distance and traveling time by using main roads and alternative routes.

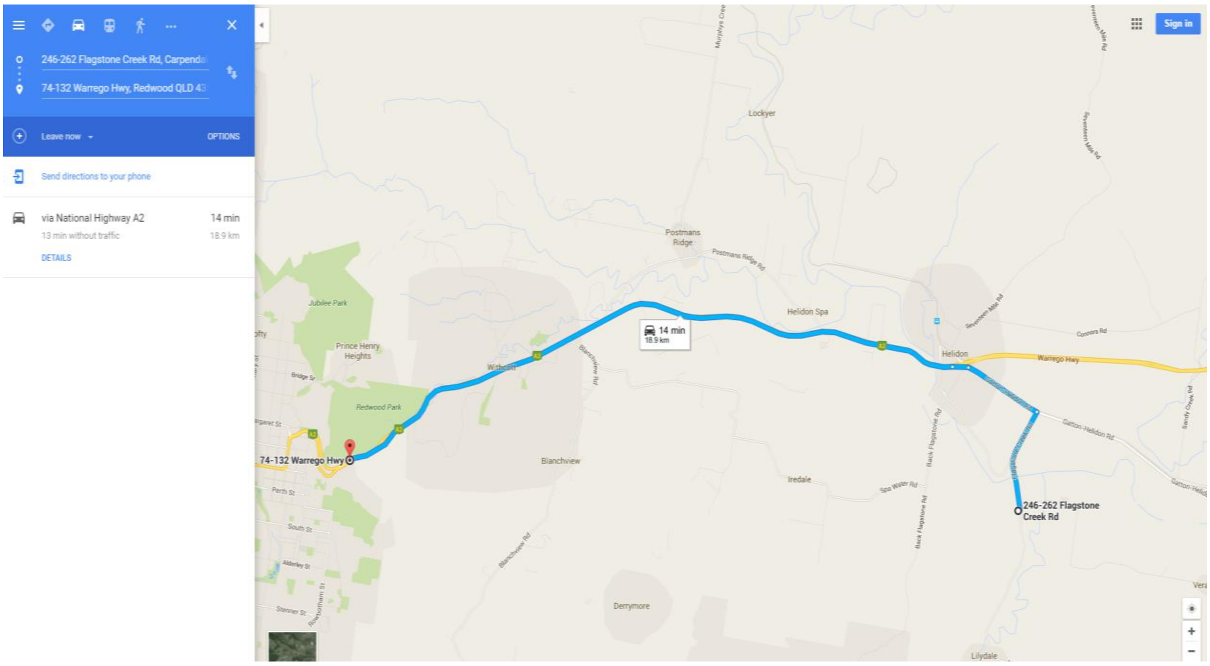


Figure 5.5 Main road traveling distance and time

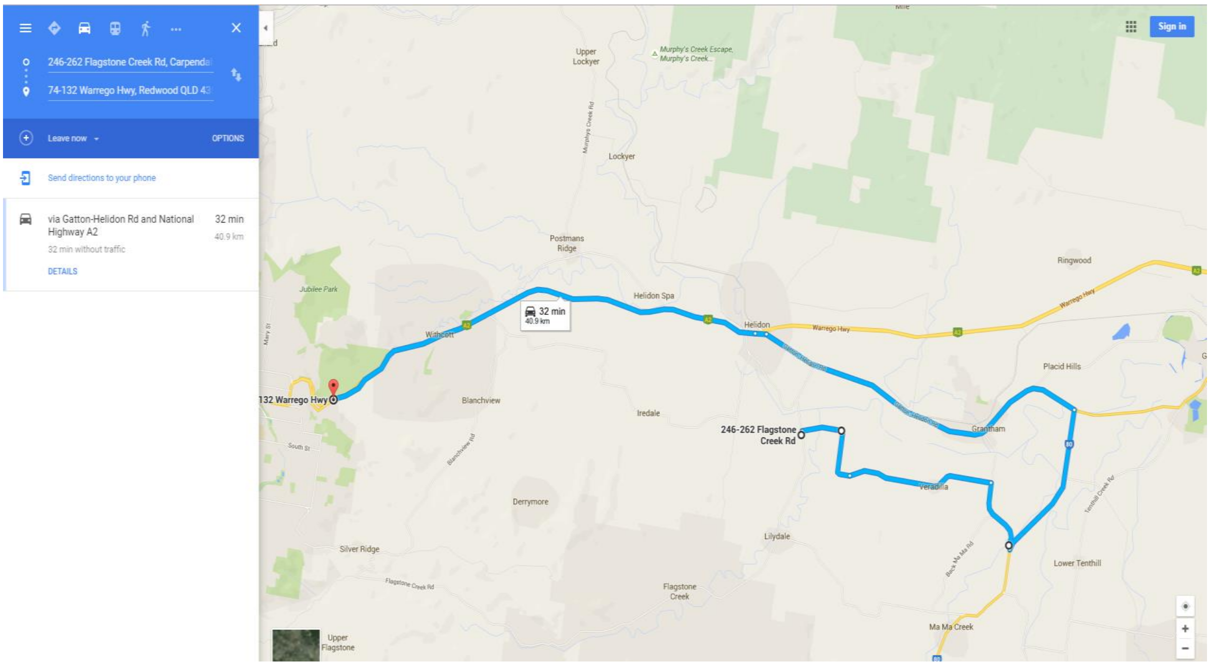


Figure 5.6 Alternative road traveling distance and time

(7) This map provides evidence for analysing traveling patterns and possible impacts on the local region. The inconveniences of an average extra traveling distance and average extra traveling time are the main impacts on residents. In this map, the majority of residents on the

northern sides of the damaged bridge would like to travel to get necessary services, and residents who live outside this region try to reach their places of work. Regarding farm and industries that are located around transportation affected region, transportation is one of the biggest problems that they should face. Their productive procedures need to get resources from outside. Transportation provides accessibility of labour in/out, products, necessary productive material, machines and other productive conditions. Sometimes, these productive conditions are allocated along with the main roads, such as water, power, internetand sewer. Others resources may also be cut off or delayed because of a delivery problem. Therefore, the potential and maximum productive capacity of farm and industry in this area will be affected by flood events. Also, their products are always delivered to the outside of local regions to different markets. There will be additional costs on the inconvenience of goods delivery. A comparison on bridge damaged roads and alternative roads allow analysing resource flow via this bridge and how to satisfy the resource demand by using alternative routes.

5.6 The Estimation of economic costs of concrete bridge damage

After preparation, different data should have been collected. The first inspection should have collected data about debris quantities, bridge damage conditions, local debris disposal costs, local vehicle operating costs, and local road networks analysis. The next step is to use this data to estimate the gross economic losses of bridge damage.

The economic losses of damages to concrete bridges in flood events are calculated by adding up direct tangible costs, direct intangible cost, indirect tangible costs, and indirect intangible costs:

$$\mathrm{C_{total}} = \sum(\mathrm{DC_{tangible}}, \mathrm{DC_{Intangible}}, \mathrm{IDC_{tangible}}, \mathrm{IDC_{intangible}}) \qquad (11)$$

Where, $\mathrm{DC_{tangible}}$= Direct tangible cost, $\mathrm{DC_{Intangible}}$= Direct intangible costs, $\mathrm{IDC_{tangible}}$= Indirect tangible costs, $\mathrm{IDC_{intangible}}$= Indirect intangible costs.

The total losses are calculated by adding up these four most important aspects. Each aspect comprises multiple costs.

5.6.1 The direct tangible costs

Direct tangible costs can be expressed as below:

$$DC_{\text{tangible}} = D_{\text{debris cleaning}} + B_{\text{recovery}} \tag{12}$$

(1) Debris clearance cost

Debris, which is wastes, caused by flood torrents can build up on upstream sides, superstructures, and connection of bridges during flood events. Debris type varies depending on the conditions of the upstream environment. Normally, debris includes vegetation (e.g. trees, limbs and grass), construction waste, municipal solid waste, unfixed household sundries (e.g. white goods), dead animals, etc. Debris clearance activities consist of debris collection, transportation, and disposal of debris (Booth 2010; FEMA 2007). As debris must be cleaned to minimize the effects of waste build-ups, the expenditures on debris removal always account for a significant part of the recovery costs after a flood event. According to FEMA 2007, expenses on debris cleaning account for 27% of the cost of disasters management (FEMA 2007).

There are inspection records and disaster records which illustrate that debris build-ups on bridges can force authorities to close them off to remove it. Otherwise, the debris and wastes created during repair and reconstruction need to be cleaned. After flood events, damaged bridge structural components need to be taken down and cleaned before repairing them (Mackie, Kevin Rory, Wong & Stojadinovic 2008). These damaged components can include damaged concrete structural components, barriers and joint seals. The damage mode on superstructures can be spallings, fragments of slabs and damaged bitumen.

In this research, costs of debris clearance can be separated into three types: (1) Debris collection, (2) Debris transportation, and (3) Waste disposal. Waste disposal can also be classified into direct tangible cost and indirect intangible cost on environmental impacts. At this stage, $D_{disposal}$ stands for costs on direct tangible costs.

In the debris cleaning progress, $D_{debris\ cleaning}$ can be expressed as:

$$D_{debris\ cleaning} = D_{collection} + D_{transportation} + D_{disposal} \tag{13}$$

Where, $D_{collection}$= costs for debris collection, $D_{transportation}$= costs for debris transportation, $D_{disposal}$= the direct costs for debris collection, and $D_{disposal}$= direct costs on direct tangible costs.

In order to estimate the different costs of debris disposal, estimating debris quantities that need to be collected is the first step. In this paper, debris quantities are mainly estimated due to inspection after a flood event. Inspectors will evaluate both debris quantities around damaged bridge and bridge damage condition. When estimating debris quantities, the first problem to solve is measuring the range of debris collection. Debris that will affect bridge recovery should be cleaned, and the cleaning range depends on the size of the bridge. Therefore, ranges will include abutment and bank areas, which are required in order to repair abutments and approach roads. Normally, debris quantities can be estimated as below:

$$Q_{Debris} = \rho_{Debris} \times V_{Debris} \tag{14}$$

Where, Q_{Debris} = Debris quantities, ρ_{Debris} = Debris density, which can be estimated by evaluating and weighing, V_{Debris}= debris volume.

Debris collection is related to debris quantities and cleaning cost quota per tonne (E_{clean}). Collection can be presented as:

$$D_{collection} = Q_{Debris} \times E_{clean} \quad (15)$$

Where, E_{clean}= the costs for collection and load debris per tonne. However, E_{clean} is not measured or provided by the contractor. In this research, it was assumed that E_{clean} is close to the costs on clear sites and site preparation in the Rawlinson handbook.

In terms of debris transportation, transportation costs are mainly vehicle operating costs and workers' salaries. The costs are related to the distance to dumping sites, routine, and truck loading per trip.

$$D_{transportation} = \sum[\,(Q_{Debris}/M_{trip}) \times C_{vehicle} \times S_{dump}] \quad (16)$$

Where, M_{trip}= average loading per trip, S_{dump}= distance from dumping sites.

This equation needs to summarize different distances from different sides of the damaged bridge to dumping sites and empty trips in which vehicles need to travel back to the damaged bridge.

$$D_{disposal} = Q_{Debris} \times C_{disposal} \quad (17)$$

Where, $C_{disposal}$= disposal cost per tonne. The debris disposal price will vary according to different debris types and state regulations.

(2) Bridge recovery

$$B_{recovery} = \sum B_{repair} + \sum B_{replacement} + \sum B_{extra\ reinforcement} \quad (18)$$

Where, B_{repair} = costs for repairing structural components of the damaged bridge, $B_{replacement}$= costs for replacing damaged structural components, and $B_{extra\ reinforcement}$= costs for extra reinforcement or improvement of the damaged bridge.

Reinforcements will include steel bracing, enlarged substructures, adding piles,etc. The additional reinforcement mainly improves and guarantees bridge stability and capacity when the existing structure is not safe enough.

With the inspection report, there will be bridge structure performance groups and the damaged stages. To recover or repair different damage performance groups, construction plans always vary due to bridge types, bridge design, surrounding environment, etc. A different repair construction plan will lead to a different construction technology and different costs. There is a detailed price index of different construction technology in Rawlinson's Australian construction handbook. Therefore, the bridge recovery costs are mainly a summary of all expenditures on different construction technology of each structure performance group.

At the stage of evaluating costs of a bridge recovery, a detailed repair and reinforcement plan may not be fully developed. In this circumstance, inspection results and possible recovery methods will lead to differences between estimated results and real costs.

5.6.2 Direct intangible losses

$\mathrm{DC}_{\mathrm{Intangible}}$ is different in this research because heritage and psychological stress will not be given fixed numbers of value.

(1) Regarding historical bridges, they have some intangible value. Some of the studies used were willing-to-pay method as the standard to measure the value of heritage (Kim, Wong & Cho 2007; Navrud & Ready 2002). Different types of survey and economic methodology will be applied. In Australia, institutions of the heritage chairs and officials of Australia and New Zealand have already carried the projects to measure historical heritages. The objective results of the historic bridge can be derived from Heritage chairs and officials of Australia and New Zealand. Despite the economic value of actual bridge damage, a brief summary of the historical building will be needed to introduce the outstanding value of this historical

heritage. Values of the heritage are interpreted as three aspects: humanities, history and bridge design:

(a) Humanities: Some bridges will have stories, or can become symbols such as the Cambridge.

(b) History: Some bridges are closely related to regional events or regional history. The First cast-iron-bridge was built over the River Severn at Coalbrookdale in 1779. It is related to the increasing traffic demand of regional industry development. That bridge reflects regional steel and transportation development. Also, it is a symbol of the industrial revolution in Coalbrookdale region.

(c) Design: Some bridges have a special value of design. First cast-iron-bridge which was built over the River Severn at Coalbrookdale in 1779, was breakthrough and innovative designing at that time. It was the first attempt to use iron to achieve great carrying capacity when stones could not be used due to the length of fly-past.

$$\mathrm{DC}_{\mathrm{Intangible}} = \mathrm{Descirbe\ contents\ (Humanities, History, Designing)} \tag{19}$$

(2) In terms of the psychological reaction of a bridge user, close observation and further research on road psychology are needed. Road psychology is a complex process and can be impacted by multiple factors. There are problems with measuring the impacts of psychological reactions. First of all, few types of research focus on drivers' psychological reaction when they face to bridge damage after flood events. There is ninety percent of local inhabitants would not cancel their trips (Zhu et al. 2010). Instead, they would change their timetable (travel earlier). When travellers realized bridge damage and impacts on their daily trips, how these travellers react and their emotion change need to be concerned. Currently, very few research focuses on address these issues. Secondly, there are no mature models to help researchers observe and record bridge users' and travellers' reactions. Under this circumstance, the model still cannot precisely predict the road users' emotional changes and reactions due to bridge closure, detours and traffic problems after disasters. Further research is still needed to estimate drivers' reaction due to different states of road damage and detours.

With current knowledge, it seems impossible to predict the consequences of drivers' emotions and reactions. Therefore, the costs of psychological impacts cannot be evaluated at this stage.

To support further research on psychological impacts, this research would like to record efforts and resources that are considered to improve guidance and traveling experiences after bridge damage. In the Lockyer Valley region, there would be temporary bridge to support small vehicles (Figure 5.7). Public resources will be invested in these aspects to improve traveling experiences after bridge damage:

Installation of abutments and the visible detour at Kirsop Bridge, Murphy's Creek

Figure 5.7 Detour support in the Lockyer Valley (Queensland Reconstruction Authority 2015)

(a) Thorough road signs and guidance to detour roads.

(b) Improved alternative roads conditions.

(c) Traffic control and traffic guidance.

(d) Broadcasted recovery plans and process to bridge users.

(e) Complaint boxes and complainant receptions to bridge users.

(f) Alternative public transportation

Also, costs on different types of efforts should also be recorded. These investments could be evidence for research on marginal costs of accessibility and traffic control when the bridge is damaged in flood events.

5.6.3 Indirect tangible costs

The gross costs of indirect tangible costs can be expressed as below:

$$\mathrm{IDC}_{\mathrm{tangible}} = \sum(\mathrm{C}_{\mathrm{detour}}, \mathrm{C}_{\mathrm{production\ capacity}}, \mathrm{C}_{\mathrm{time}}) \tag{20}$$

Where, $\mathrm{C}_{\mathrm{detour}}$= Costs for taking a detour, $\mathrm{C}_{\mathrm{production\ capacity}}$ = costs for lost production capacity, and $\mathrm{C}_{\mathrm{time}}$= opportunity costs for the extra time that is spent on a detour.

The total costs of indirect tangible costs include gross vehicle detour costs, losses of the productive capacity of industry and manufacture and opportunity costs of time which is wasted during the period when the bridge is down.

(1) Costs for detour

$$\mathrm{C}_{\mathrm{detour}} = \mathrm{S} \times \mathrm{C}_{\mathrm{vehicle}} \times \mathrm{N} \times \mathrm{t} \tag{21}$$

Where, S= average detour distance, $\mathrm{C}_{\mathrm{vehicle}}$=vehicle operating costs per Km, N= average vehicles volume, and t= time periods that bridge users have to detour.

(2) Losing production capacity

$$C_{\text{production capacity}} = \alpha_{\max}\,(1-\Delta\,)P^{\text{ini}} \tag{22}$$

Where, P^{ini}= the pre-event production capacity, $\alpha_{\max}$= the maximum production capacity, and Δ= loss of production capacity.

$$\Delta = \text{Max}\left(\frac{S_r - S_s}{S_r}\right) \tag{23}$$

Where, S_r= resource needed for daily production, and S_s= resource that can be supplied after the bridge damage.

In production progress, different production conditions and preparations will be required so as to achieve production capacity. In the inventory input-output model, all production conditions are considered as inventory for production. Insufficient productive capital will lead to a decrease in production capacity. When a local industry is not able to produce enough to satisfy the local market, the gross added value of output reduction is the loss in disasters (Hallegatte 2014). However, bridges and other road infrastructure are not the only factor that prevents local industries from obtaining productive capital required. There are dozens of problems that negatively affect industries' production capacity, such as damaged machinery, power, water and communications networks. Although transportation and accessibility problems will impact the recovery of other infrastructure and indirectly affect production capacity (Dalziell & Nicholson 2001), reductions in gross output reduction are not caused only by them. At this stage, bridge damage decreases industries' production capacity by impacting associated facilities. Productive capital dependent on transportation and accessibility are workers, raw materials and power. The Δ is given by the maximum value of all resource constraints related to the transportation damage.

(3) Opportunity costs of extra traveling time:

$$C_{\text{time}} = \sum_{i=0}^{n} T_{\text{traveling}} A_{\text{average}} \tag{24}$$

Where, $T_{traveling}$= Average extra time on detouring, and $A_{average}$= average salary of traveller. This equation calculates the opportunity cost of detouring. However, the opportunity cost of time varies from person to person. Individuals earn different salaries and create different amount of value per hour. However, it is hard to calculate the value that different employees create per hour. In this paper, the opportunity cost is defined as the average regional salary.

5.6.4 Indirect intangible costs

$$IDC_{intangible} = C_{trust} + C_{labour} + C_{Envrionment} \quad (25)$$

Where, C_{trust}= value of loss of confidence and trust in authorities, C_{labour}=Economic impacts of local labour markets and unemployment, and $C_{Environment}$= debris has intangible impacts on surrounding environment.

(1) C_{trust} is a phenomenon that could happen during road infrastructure recovery. This phenomenon is summarized from interview of CRC (Jane Mullett 2015; Setunge et al. 2015). Residents and bridge users may show distrust toward the local council. They will query and suspect the decisions and plans from the local council when they are not well involved in the recovery process. The causes of trust crisis are the transparency of information about repair plans and process, adopting a suggestion from residents, a lack of communication between local council and residents, rejecting participation of local residents ,etc. The local council focus on their duty and recovery work and ignore their intection with stakholders of bridge. In Australia, there are comprehensive instructions and strategies for local council to help people affected by natual disaster in different areas (Matthews et al. 2002; Winkworth 2007). These instructions and strategies emphasise importantce of timely (in that assistance is provided when it is needed and for as long as it is needed), proactive (being actively involved in planning for a range of options) and accessible (developing creative strategies to ensure people are able to receive assistance) (Winkworth 2007). Efforts and works that are made by the local council should meet the expectation of the local residents. When the local residents

and stakeholders of bridge are not satisfied with work that are made by the local council, the local council would lose their authority.

In the case study in chapter 6.6.4, the local council in Lockyer Valley would be used to illustrate the gap between their work and expectation of local residents. The local council has taken lots of measures during birdge damage. The local residents appreciated the work that has been made by the local council. However, the stakeholder of bridge still not satisfied with information transparency, participation in recovery work and rigid rules of help center.

The social trust has potential to impact future community work. In this research, the value of social trust can be presented as the resources used to maintain the authority of the local council. Resources are the costs of involving residents and bridge users in bridge recovery progress. Necessary works include information disclosure and communication, hearing and answering questions about the recovery plan, complainant reception, responding to complaints, etc. In this research, the costs for these activities are considered as the expenditures on information transparency and communication.

$$\mathrm{C_{trust}} = \sum_{\mathrm{i=0}}^{\mathrm{n}} \{\mathrm{A_1, A_2, A_3, A_4} \cdots\} \tag{26}$$

$\mathrm{A_1, A_2, A_3}$ and $\mathrm{A_4}$ stand for the costs of different activities to improve the participation of bridge users and local inhabitants, information disclosure, and communication. This equation will be the summary of the total costs and efforts in maintaining the local council authority.

(2) $\mathrm{C_{labour}}$ is changed and the change in the labour market can be observed after flood events. The general trend of regional employment decreases by 3.4% on average after flood events (Sarmiento 2007). It also claims that bridge availability and accessibility will have negative impacts on the local employment market (Enke, Tirasirichai & Luna 2008). Unemployment is a result that is caused by integrated factors. Bridges and other road infrastructures are only one part of the reasons. On the other hand, construction and construction related business are grown due to repair and rehabilitation work after flood events. Bridge inspection, repair, and

reconstruction will create job opportunities in the local labour market. It is easy to observe and compare changes in the labour market after disasters. However, it is hard to identify reasons for the unemployment of each person. Also, the economic costs of labour market fluctuation after disasters are hard to predict. In this research, further study and analysis are recommended in order to clarify relationships between bridge damage and a regional job market.

(3) In this part, environmental impacts of debris disposal can be translated to market value. The intangible value will be measured by two methods: Firstly, greenhouse gas emissions are measured by using the preventive-expenditures method, involving the price of purchasing greenhouse credits. Secondly, other gas emissions are measured by the potential damage value of emission per unit into the air. Costs can be summarized in the following way:

$$C_{\mathrm{Environment}} = C_{\mathrm{Greenhouse}} + C_{\mathrm{other\ emission}} + C_{\mathrm{leachate}} + C_{\mathrm{Amenity}} \qquad (27)$$

Where, $C_{\mathrm{Greenhouse}}$= the cost of greenhouse gas emissions from per tonne of source (debris), $C_{\mathrm{other\ emission}}$= the cost of other gas emissions such as SOx, NOx, VOC, lead, CO, ioxins, etc., into the air per tonne of source (debris), C_{leachate}= the cost of pollutants and emissions into water, which occurs when liquid passes through a landfill, per tonne of source (debris), and C_{Amenity} = cost of inconvenient impacts, including noise, dust, litter, odour and pests on local communities per tonne of source (debris).

CHAPTER6 CASE STUDY

6.1 General condition of case study

The Kapernicks Bridge is a small bridge that is Located on the Flagstone Creek RD and crossing the Lockyer Creed River. It was built on 1st January 1981 with the length of 66.1m and the width of 7.6m. It is a three-span, two-lane precast concrete girder bridge. There was no expectation for pedestrian use. Therefore, there is no footpath in this bridge and steel barriers were designed only for traffic. It comprises four precast concrete girders that are supported by two abutments and two piers with a cast-in-situ headstock and four cast-in-situ piles. There are cast-in-situ kerbs on the left-hand side and right-hand side. This bridge suffers several flood events. Different structure components of this bridge suffered different extent damage after flood events. These structure components had been repaired after flood events. In 2011 flood events, one side of bridge abutment was impacted by a floating container and severely damaged. Superstructures, piles and abutment were damaged. The strength and stability of bridge body were impaired. On the same side, approach road, roadbed, and riverside were swept. Structures and approach roads were repaired after flood events. After repair, further inspection and appraisement were conducted in March 2012. Considering structure strength, safety and reliability of the bridge, local community added steel bracing to damaged bridge in April 2012. Around 2/3 of the bridge stress members were reinforced. In conclusion, this bridge was repaired, and some of its structures were improved. Steel bracing is the consequence of bridge damage in this case. After repair, inspection and assessment, it pointed out that repair cannot sufficient support bridge loading. Steel bracing was needed to improve structure strength. Steel bracing plan was considered as a part of bridge recovery.

Kapernicks Bridge is important to the local community. It is located at a prominent location: On the south of the bridge, there are farms and some meat industries. On the north of the bridge, there are main cities, fuels, markets and services. More importantly, this bridge is the main routine to majority farmers, industry, and residents. Service, commodities, productive material and workers are travel into the local community, while agricultural products and residents travel out of traffic affected region. Compare with alternative bridges, it has greater traffic volume. It is faster and more convenient way to cargo, commuter and collective activities. Therefore, this bridge is important to support regional accessibility.

6.1.1 Objectives of the case study

The integrated models will be validated in this case study. It will start from very first step to collect data and estimate all types of economic impacts. Results and progress, which can be finished in this case study, will provide references for further research. Main targets of this case study are as follows:

(1) Set proper performance groups of damaged bridge structure components and describe damage states properly.

(2) Collect regional traffic information to estimate local vehicle operating costs for different types of vehicles.

(3) Debris disposal costs should be estimated due to debris quantities, regional charge information, and elimination methods.

(4) Regional road system maps should be established to sufficiently support road network identification, identifying traffic affected region and identifying alternative routes.

(5) Estimate bridge recovery costs due to different damage states of bridge performance groups, repair methods and regional price level.

(6) Estimate costs on detour of bridge user and possible decreasing industry productive capacity.

(7) Interpreting historical value of bridge and recommended resources that can be used to release road psychological problems.

(8) Interpreting how the local council will lose confidence/trust and how to use resources to release impacts.

(9) Identifying possible potential change on labour market

(10) Estimate the environmental economic impacts of debris disposal

6.1.2 Data sources and the main constraints

Research always lacks efficient, detailed, comparable, reliable and comprehensive data to support a comprehensive case study (Meyer et al. 2013). Data efficiency, data availability and data collection will also constrain this case study.

First, data needs to be collected from different sources, which means that different types of data are collected for different purposes. There could be some problems that can impact accuracy of estimation:

(1) Some information may not be a detailed record because it seems useless for other research or purposes (Downton & Pielke 2005). Different institutions collect data by preferences. For example, the debris quantity that is around the damaged bridge is not estimated or mentioned.

(2) There are different standards for different institutions to collect data. These data would not satisfy particular research purposes. For example, economic impacts that are collected by insurance companies only cover insured properties. Insured properties in flood events account for only ten percent of total losses (Gentle, Kierce & Nitz 2001).

(3) Some types of data such as reports and drawings are belonged to different institutions. This information can be accessed when authority is approved by different institutions such as designing company and the local council.

(4) File management is a challenge for disaster-related documents. There were three continuous flood events in 2008, 2011 and 2013. Lots of papers and records need to be collected and managed for this period.

Secondly, data is also constrained by the time horizon. That means some data cannot be collected after the bridge is recovered. For example, debris quantities on alternative roads, rock backfill quantities, materials that flow in/out from the damage affected region. This type of information has obvious time limits. Accurate information cannot be derived when data has not been recorded after flood events. Some data will be lost due to document management and reservation.

In this case study, first-hand data is obtained from the local council is still not enough to support this case study. To reduce the impact of the data constraints on the case study, some corrective measures will be taken to finish this case study. First, some types of information are derived from estimation that is based on inaccurate and non-detailed records. In this case study, the inspection report, images, and repair drawing will provide information to estimate debris quantities and the states of damage of the girders. These estimations will be based on pictures, evaluations, and the memories of members of the local council. Secondly, some data will be derived from similar research or databases. In this case study, the constitution of vehicles in Locker Valley is not detailed enough. The constitution of Queensland is introduced to help estimate vehicle constitution. Some other vehicle tech specs that are considered important to economic impact estimation would be derived from research that focuses on vehicles.

6.2 Bridge performance group and damage states of performance groups

In order to evaluate the bridge damage states of different bridge structures, bridge body and structures will be broken down into different performance groups. Also, different identifications will be given to locating each performance group. In this case study, bridge performance groups should be separated into six classes, and identification sequences will start from one side to the other side. All bridge structure components in this bridge are included in performance groups, such as undamaged and unrepaired bridge structure components.

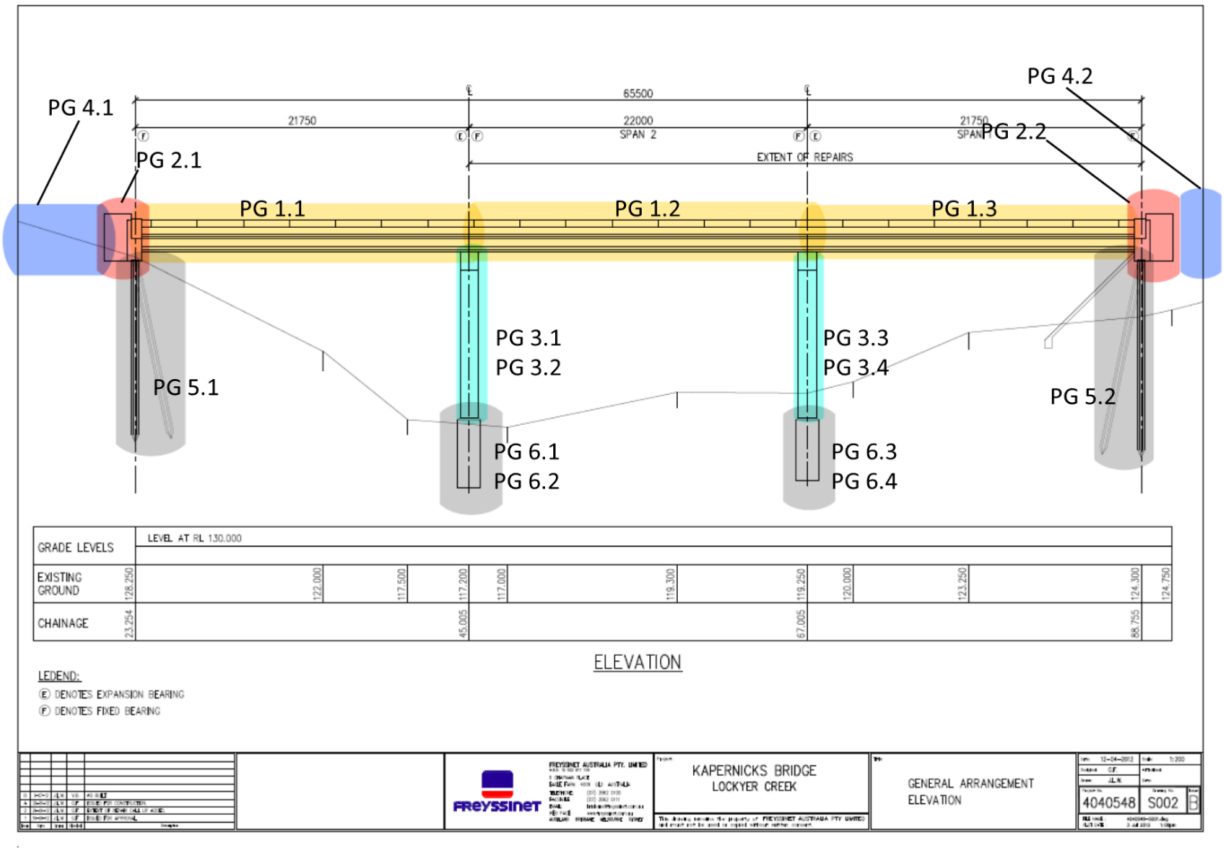


Figure 6.1 Performance group sketch map

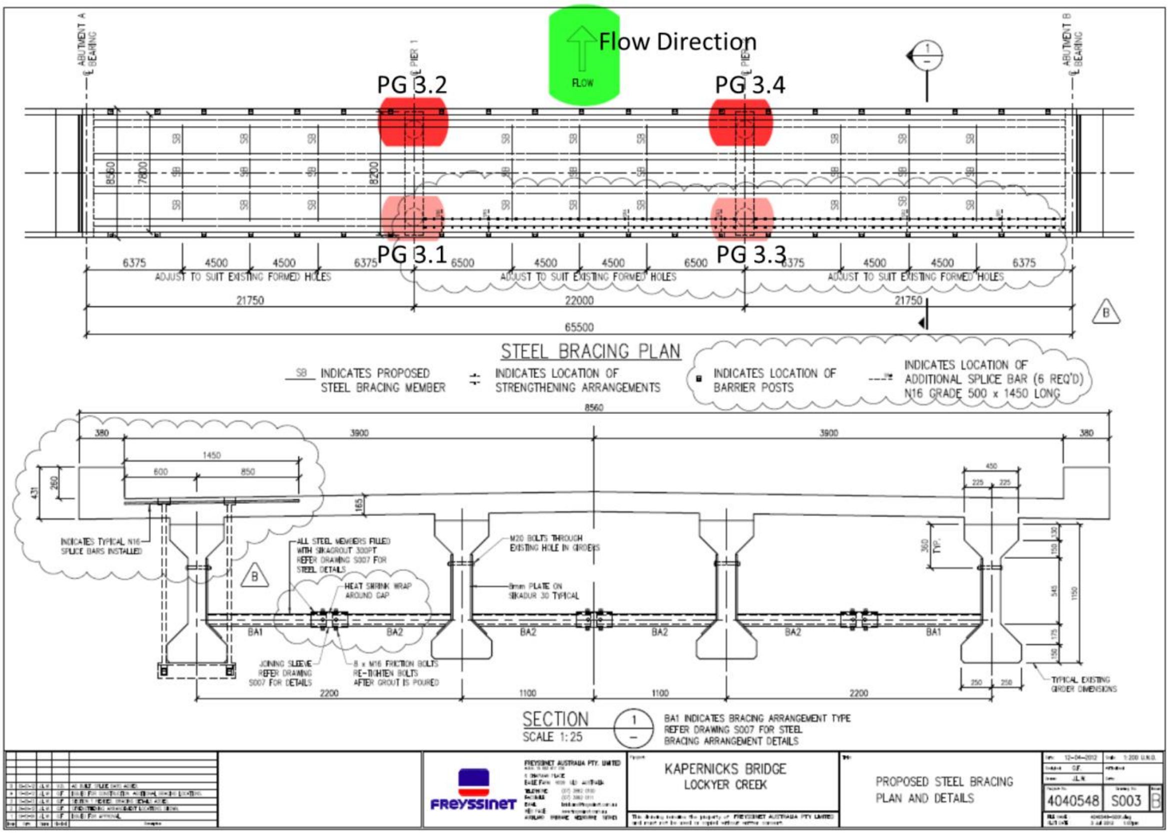


Figure 6.2 Flow direction and column position

According to the drawings, all performance groups can be summarized as below:

Table 6.1 Superstructure performance groups

Name	ID	Location Description
Superstructure	PG 1.1	The first span from left sides from upstream view
	PG 1.2	The second span left sides from upstream view
	PG 1.3	The third span from left sides from upstream side

Table 6.2 Abutment performance groups

Name	ID	Location description
Abutment	PG 2.1	Abutment on the left side from upstream side
	PG 2.2	Abutment on the right side from upstream side

Table 6.3 Column performance groups

Name	ID	Location Description
Column	PG 3.1	First column at first row from the left sides from upstream side
	PG 3.2	First column at second row from the left sides from upstream side
	PG 3.3	Second column at first row from the left sides from upstream side
	PG 3.4	Second column at second row from the left sides from upstream side

Table 6.4 Approach road performance groups

Name	ID	Location Description
Approach road	PG 4.1	Approach road on left from upstream side
	PG 4.2	Approach road on right from upstream side

Table 6.5 Abutment foundation performance groups

Name	ID	Description
Abutment foundation	PG 5.1	Abutment foundation on left from upstream side
	PG 5.2	Abutment Foundation on right from upstream side

Table 6.6 Column foundation and piles performance groups

Name	ID	Description
Column Foundation and piles	PG 6.1	First column foundation at first row from the left sides from upstream side
	PG 6.2	First column foundation at second row from the left sides from upstream side
	PG 6.3	Second column foundation at first row from the left sides from upstream side
	PG 6.4	Second column foundation at second row from the left sides from upstream side

From now on, each performance group has been given an identification and a location information. The next stage is to interpret damage states of each performance group. The description would be transferred from inspection report into different damage states. In this research, damage states could be summarized from two aspects:

(1) Estimating damage states relies on observation from images and periodical inspection reports. At this stage, some first inspection reports, repair plans, and drawings about 2011 flood events are significant evidence.

(2) Damage states are also summarized from the fieldwork. The local council provided information about post-disaster conditions about bridge and surrounding roads. Also, steel bracing and bridge conditions were observed personally in the Lockyer Valley region. There are some photos that were collected from the local council and residents:

Figure 6.3 Inspection photos after the 2011 flood events (Provided by Lockyer valley council)

6.2.1 Damage states of Kapernicks Bridge

Different damage states of performance groups can be observed after the 2011 flood events. Frankly, the first span of bridge including PG 1.1, PG 2.1, PG 4.1 and PG 5.1, seems in good condition according to the inspection report after the 2011 flood events. There were few records of repair or reinforcement for the first span. The only change in the first span is that stocks are used to protect approach roads and riverbanks after flood events. In contrast, records of inspection and repair show that structures in the second span and third span were damaged severely in the 2011 flood event. Different structural components were repaired, replaced and reinforced. There was also aggradation and degradation during the 2011 flood events. Debris, soil and small stones were built up on the upstream side of the bridge. The river bottom and riverbanks were degraded severely. The damage states of each structural component, which were derived from the second and third inspection reports and images can be summarized as below:

(1) The Superstructures

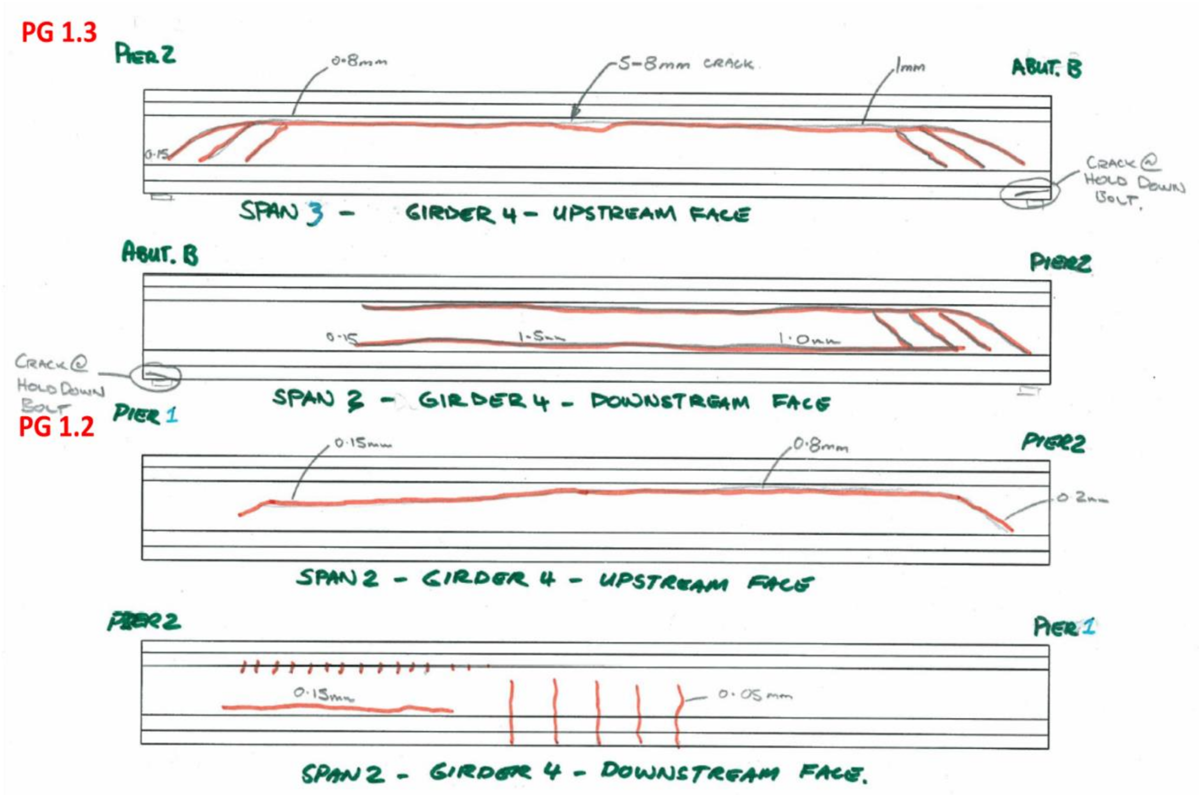


Figure 6.4 Sketch map of cracks (2012 Inspection report by R.Greg Eberh)

The girders are the structural components that were mainly damaged in the 2011 flood events. This part were detailed mentioned by the second inspection report and the steel bracing plan.

Table 6.7 Damage states of superstructures

ID	Damage states	Detailed damage information
PG 1.1	No damage	Small old cracks which seem created in the past
PG 1.2	Ds 2	No signs of new cracks and crack patterns were observed on concrete deck slab. However, there are different widths longitudinal cracks that can be seen from girders. There are 4m cracks (averaging 0.8mm to 0.9mmm over mid-span), 4m cracks with 0.15mm width, short, distinct cracks (30mm apart, 50mm long). Old vertical cracking appeared through midspan of the girder (5 off, 1m apart; 10 off, 1m apart and 7 off, 1m apart). That means this bridge has been overloaded in the past.
PG 1.3	Ds 3	No signs of cracking were evident on the deck slab. However, this span suffers impacts of the container and had significant cracking along the web of the I-beam on both faces. There are approximately 4m cracks (averaging 5mm over mid-span) on both sides. Minor lateral movement between the two sides of the cracks was noted (less than 1mm). Also, there are spalls on the pier which is assumed as a result of impact.

Repair:

Significant cracks can be repaired by injection methods. However, the cracks on girders in performance group 1.3 (PG 1.3) were considered to decrease strength and reliability after flood events. Girders located on the upstream sides of PG 1.2 and PG 1.3 were considered vulnerable and not strong enough to support the superstructure safely. In addition to mending cracks on girders, steel bracing is used to improve the carrying capacity of the bridge. Also, steel diaphragms were used throughout the mid-span section between each grid.

(2) Abutment

Table 6.8 Damage states of the abutment

ID	Damage states	Detailed damage information
PG 2.1	DS 1	Spalling was apparent under the pedestal anchor bolt. Cracks were observed. Bearings were in sound condition.
PG 2.2	N/A	No sign of new damage

Repair:

Bolts and angles need to be removed. The injection would be applied to repair cracks. Units will be jacked, and bearings should be removed to rectify girders.

(3) Column

Table 6.9 Damage states of column

ID	Damage states	Detailed damage information
PG 3.1	NO damage	No sign of new damage
PG 3.2	NO damage	No sign of new damage
PG 3.3	Ds 1	Cracks and spalls can be observed.
PG 3.4	NO damage	No sign of new damage

(4) Approach roads

Table 6.10 Damage states of approach roads

ID	Damage states	Detailed damage information
PG 4.1	No damage	Approach road seems not damaged. However, soils in riverbank that are around approach road were washed away. To maintain the riverbank, stocks are backfilled around these areas.
PG 4.2	Ds 4	Approach road, including subgrade and parts of riverbank, were eroded and washed away during flood events.

Repair:

Riverbank were backfilled with stocks. Moreover, riverway and riverbank were strengthened by stocks. After backfill, approach roads were rebuilt to connect bridge and road networks.

(5) Abutment foundation

Table 6.11 Damage state of abutment foundation

ID	Description	Detailed damage information
PG 5.1	No damage	Surrounding soil was swept.
PG 5.2	Ds4	Surrounding soil was swept. Abutment foundation was exposed.

Due to limits of inspection reports, there is not enough evidence to estimate damages on abutment foundations. Lateral and vertical drifts were not recorded in the inspection report. It is hard to predict the impacts on stability and reliability. Also, the repair plan and steel bracing did not mention any repair or reinforcement measures. It seems that the Abutment and abutment foundation were not significantly damaged in the 2011 flood event.

The Photos (Figure 6.5) below are the comparison before and after repair. The foundation and its surroundings were reinforced after the bridge repair.

Figure 6.5 Conditions of bridge foundation after 2011 flood event (From Locyer valley city council)

Figure 6.6 Conditions of abutment foundation after recovery (From Lockyer Valley city council)

(6) Column Foundation

Table 6.12 Damage states of column foundation

ID	Description	Detailed damage information
PG 6.1	No damage	No sign of new damage
PG 6.2	No damage	No sign of new damage
PG 6.3	No damage	No sign of new damage
PG 6.4	No damage	No sign of new damage

There was no sign of new damage on the column foundation in the inspection report. In addition, drift ratio and displacement were not available. No evidence showed that there was either a repair or a reinforcement on the column foundation.

In this case study, some damage states of performance groups are not available due to data limits.

(1) Certain kinds of information were not collected after the flood events. (2) Some reports and information have expired or were missing during this period. The lack of accurate and related data becomes a factor that will constrain the accuracy of the damage state estimation. At this stage, only limited data is available:

(1) Second inspection report of girder after flood events;

(2) General inspection reports from 2014;

(3) Steel bracing drawings of girder;

(4) Post-disaster images;

(5) Information and photos that are collected by fieldwork.

6.3 Regional vehicle operating costs

In this case study, this model is used to adjust regional data to estimate the vehicle operating cost of each vehicle type. Information about vehicles on road around the Lockyer Valley region needs to be collected. Regional operating expenses of vehicles should collect data about vehicle usage, regional preference, traffic volume and traffic constitute. Regional vehicle condition will be affected by population density, local road condition, requirement, and topography. Three steps are introduced to prepare information for estimating regional vehicle operating costs:

(1) Collect local traffic information including traffic constitutes/rates, traffic volume, fuel types of vehicles, average loadings and the average purchasing price of each type of vehicle.

(2) Group different types of vehicles. Different characters can be used to distinguish different vehicles. Fuel types and vehicle dimensions must be considered at first. The costs with different fuel types and vehicle classes are entirely different. In order to achieve a more accurate result, some parameters can be used to classify vehicles more precisely. Basically, classification will depend on traffic volume. Great volume number allows getting more

vehicles groups. More accurate dimension classification, purchase price, frontal area and air drag coefficient could be used to get more vehicle groups.

(3) Introduce proper parameters to each group of vehicles. There will be different tech specs for different types of vehicles. In same vehicle group, parameters could vary from brand to brand. The majority types of vehicles would determine the mean value. To get a representative value, it is better to use a weighing value to calculate the weighted average value for each parameter.

In this case study, regional vehicle data is applied. According to the local council, the traffic flow of Kapernicks bridges, which was collected in 2006, is, on average, 729 per day with 26.5 % of these being heavy vehicles. After the flood event, the traveling demand of Kapernick Bridge was also assumed as 729. There are two reasons: (1) Generally, around 92% of average individuals would continue their daily trips even after a bridge collapse (Xie & Levinson 2011). That means that the traveling demand of the damaged bridge will not decrease. (2) There would be an increase in engineering and heavy vehicles that use the Kapernicks bridge to access both sides of the bridge. This research assumed that an increased number of engineering vehicles would not change the regional traffic number a lot.

In this case study, vehicles are separated into five groups: (1) private petrol vehicles; (2) private diesel vehicles; (3) light commercial petrol vehicles; (4) light commercial diesel vehicles; (5) heavy duty vehicles.

Reasons for group settings are as follows: (1) the traffic volume is relatively small. Too many group settings would lead to inefficient sample numbers in each cluster. (2) There is a data limit. Vehicle information is not detailed enough to set more groups. There should be a detailed record of vehicle constitution to set more vehicle groups.

To measure operating costs of each group of vehicles, different parameters should be applied in regional operating costs model. For each group of vehicles, parameters will distinguish costs in different aspects. There are 27 parameters that will significantly impact vehicle operating costs. In this case study, the regional value should be adjusted to get more accurate results. However, some values cannot be derived from local documents due to data collection limits. In order to solve data problems, the majority of parameters and values are derived from Australian Bureau statistics, literature review, and Commonwealth bank. Others can be collected from different related vehicle websites, technical specs data and market information. There are three tables that summarize all associated values that are required to measure each group of vehicle operating costs. The source of parameters also included in these chart (Table 6.13, Table 6.14, Table 6.15). Values are provided as below:

Table 6.13 Variables for private vehicle operating costs

Vehicle Operating cost variables	Units	Low	High	Average	Source
Gross Vehicle Weight	Kg	1500	2500	2000	(Australian Bureau of Statistics 2015)
Coefficient of rolling resistance	dimensionless	Asphalt 0.03 Concrete 0.01	Asphalt 0.03 Concrete 0.015	Asphalt 0.03 Concrete 0.013	(HPWizard 2016)
Coefficient of road roughness	dimensionless	0.9	1.2	1	(Akcelik & Besley 2003)
Coefficient of aerodynamic drag	dimensionless	0.25	0.45	Majority of sedan are around 0.35	(Ecommodder 2010; HPWizard 2016)
Vehicle frontal areas	m2	1.8	2.3	2.45	(Ecommodder 2010) (HPWizard 2016)
Coefficient of engine efficiency	dimensionless	Petrol 20%	Petrol 30%	25%	(Vehicle Technologies Office 2013) (U.S. department of energy 2015)
Coefficient	dimensionless	0.8	0.95	0.9	(Akcelik &

of transmission efficiency					Besley 2003)
Coefficient of differential efficiency	dimensionless	0.8	0.95	0.9	(Akcelik & Besley 2003)
Fuel energy Content	KJ/L			Petrol 3.42*104 Diesel 3.86*104	(Australian Institute of Energy 2015)
Fuel cost	AUD/L			Petrol1.422 Diesel1.483	(Australian Institute of Petroleum 2011)
Tire costs	AUD	75	200	137.5	Market price
Number of tires per vehicle	Dimensionless			4	
Life span of tires	km	40000	70000	50000	Recommended
Vehicle maintenance costs	AUD			2500	(Commbank 2012)
Oil change Costs				80	Market price
Oil change frequency	km	5000	15000	10000	recommended
Vehicle service life	Year			15	
Vehicle capital costs	AUD	26000	80000	Majority average around 35000	Toyota Holden And Ford
Vehicle Salvage value		25%	30%	27.5%	
Annual kilometres travelled	km			16300	(Australian Bureau of Statistics 2015)
Registration and insurance costs	AUD			800	(Commbank 2012)
Average vehicle operating speed	km/h	40	60	50	Field work data

Coefficient of road stiffness	dimensionless	0.9	1.15	1	(Akcelik & Besley 2003)
Road roughness maintenance factor	dimensionless	0.8	1.2	1	(Akcelik & Besley 2003)
Fuel type				Petrol 80.6% Diesel 19.4%	(Australian Bureau of Statistics 2015)
Air density	Kg/m3	1.1455 (35℃)	1.2041(20 ℃)		(The Engineering ToolBox 2010)
Discount rate				9%	(Commbank 2012)

Table 6.14 Variables for light commercial operating cost

Vehicle Operating cost variables	Units	Low	High	Average	Source
Gross Vehicle Weight	Kg			3650	(Australian Bureau of Statistics 2015)
Coefficient of rolling resistance	dimensionless	0.008	0.015 (Wong 2001)	0.012	(CATHI 2011; HPWizard 2016)
Coefficient of road roughness	dimensionless	0.9	1.2	1	(Berthelot, CF et al. 1996)
Coefficient of aerodynamic drag	dimensionless	0.3	0.75	Around 0.4	(GMC Savana 0.47 and Toyota Tarago 0.31) (HPWizard 2016; ToolBox ; Workshop 2002)
Vehicle frontal areas	m2			3.35	(GMC Savana 0.47 and Toyota Tarago 0.31) (HPWizard

					2016; ToolBox ; Workshop 2002)
Coefficient of engine efficiency	dimensionless	Petrol 20%	Petrol 30%	Petrol 25%	(Vehicle Technologies Office 2013) (U.S. department of energy 2015)
Coefficient of transmission efficiency	dimensionless	0.8	0.95	0.9	(Akcelik & Besley 2003; Berthelot, CF et al. 1996)
Coefficient of differential efficiency	dimensionless	0.8	0.95	0.9	(Akcelik & Besley 2003; Berthelot, CF et al. 1996)
Fuel energy Content	KJ/L			Petrol 3.42*104 Diesel 3.86*104	(Australian Institute of Energy 2015)
Fuel cost	AUD/L			Petrol 1.422 Diesel 1.483	(Australian Institute of Petroleum 2011)
Tire costs	AUD	90	370	Majority 230 AUD	Market value for Common tires
Number of tires per vehicle	Dimensionless			4	
Life span of tires	km	40000	70000	50000	Recommended
Vehicle maintenance costs	AUD			0.085 AUD/km	(Transport and Main Roads 2011)
Oil change Costs				80	Market Value
Oil change frequency	km	5000	15000	10000	Recommended
Vehicle service life	Year			15	
Vehicle capital costs	AUD	31000	80000	Around 50000	Price for light commercial vehicles like Toyota
Vehicle Salvage		25%	30%	27.5%	

value					
Annual kilometres travelled	km			16300	(Australian Bureau of Statistics 2015)
Annual licence and insurance costs	AUD			2000	Market Price
Average vehicle operating speed	km/h	40	60	50	Field work statistics
Coefficient of road stiffness	dimensionless	0.9	1.15	1	(Berthelot, CF et al. 1996)
Road roughness maintenance factor	dimensionless	0.8	1.2	1	(Berthelot, CF et al. 1996)
Fuel type				Petrol 55.7% Diesel 37.7% Hybrid 6.6%	(Australian Bureau of Statistics 2015)
Air density	Kg/m3	1.1455 (35 ℃)	1.2041 (20 ℃)		(The Engineering ToolBox 2010)
Discount rate				9%	(Commbank 2012)

Table 6.15 Variables for heavy commercial operating costs

Vehicle Operating cost variables	Units	Low	High	Average	Source
Gross Vehicle Weight	Kg	36000	43000	39500	(Commbank 2012)
Coefficient of rolling resistance	dimensionless	0.0045	0.008	0.0065 Data from HP WIZARD is 0.008	(HPWizard 2016)

Coefficient of road roughness	dimensionless	0.9	1.2	1	(Berthelot, CF et al. 1996)
Coefficient of aerodynamic drag	dimensionless	0.5	0.9	Majority could be 0.75	(HPWizard 2016)
Vehicle frontal areas	m2	9	10.5	Around 10	(Giannelli et al. 2005)
Coefficient of engine efficiency	dimensionless	42%	43%	42% based on heavy trucks 2010 baselines	(Vehicle Technologies Office 2013)
Coefficient of transmission efficiency	dimensionless	0.8	0.95	0.9	(Berthelot, CF et al. 1996)
Coefficient of differential efficiency	dimensionless	0.8	0.95	0.9	(Berthelot, CF et al. 1996)
Fuel Energy Content	KJ/L			Petrol 3.42*104 Diesel 3.86*104	(Australian Institute of Energy 2015)
Fuel cost	AUD/L			Petrol1.422 Diesel1.483	(Australian Institute of Petroleum 2011)
Tire costs	AUD	500	1000	750	Market price
Number of tires per vehicle	Dimensionless	20	32	26	
Lifespan of tires	km	150000	200000	175000	Recommended
Vehicle maintenance costs	AUD	11000	15000	13000	(Freight Metrics 2015)
Oil change Costs				200	Market price
Oil change frequency	km	25000	50000	25000	Recommended
Vehicle service life	Year			15	
Vehicle capital costs	AUD	210000	510000	Around 360000	(Freight Metrics 2015)
Vehicle Salvage		25%	30%	27.5%	

value					
Annual kilometres travelled	km			63400	(Australian Bureau of Statistics 2015)
Annual Registration and insurance costs	AUD	Insurance 7000/12000 AUD Registration 7000	Insurance 17000 Registration 14000	Insurance 13500 + Registration 10500	(Australian Bureau of Statistics 2015)
Average vehicle operating speed	km/h	40	60	50	Field work statistics
Coefficient of road stiffness	dimensionless	0.9	1.15	1	(Berthelot, CF et al. 1996)
Road roughness maintenance factor	dimensionless	0.8	1.2	1	(Berthelot, CF et al. 1996)
Fuel type				Diesel 99.5%	(Australian Bureau of Statistics 2015)
Air density	Kg/m3	1.1455(35℃)	1.2041(20 ℃)		(The Engineering ToolBox 2010)
Discount rate				9%	(Commbank 2012)

Vehicles are divided into private vehicles, light commercial vehicles, and heavy-duty vehicles in this research because the daily traffic via Kapernicks Bridge is only 739 vehicles. Fewer vehicle groups will lead to a large gap between lower and higher values for each type of vehicle. For example, frontal areas differences between small private vehicles and large vehicles, price differences between regular cars and luxury cars, vehicle weight differences between small vehicles and large SUVs, etc. These factors can affect vehicle operating costs in terms of fuel consumption, tire price, insurance cost and salvage value. In the end, these factors will impact the average value of vehicle operating costs. By contrast, if the bridge is located at a vital position and has large traffic numbers, for example, the West Gate Bridge in Melbourne, it is allowed for the separation of vehicles into more groups according to type, price level, design, performance, size, usage, and average loading per trip. Division into more vehicle groups can improve the estimation accuracy. However, there would be higher workload in terms of data collection, information screening, and estimation.

In this case study, mode and average values are applied to get representative values. First of all, there are different vehicle preferences in different regions. There would be two or three more popular brands and models that would account for a large percentage in one vehicle group. Secondly, a weighted value, for example, percentage, will be given to these representative models and other models to evaluate average values.

There are also some problems with values that are introduced in this case study. Some of these values varied a lot in different occasions. L_{total}, which is the total mechanical efficiency, is hard to measured. This value is varied due to different engine type, year of manufacture, brand and vehicle type. In addition, their standards of total mechanical efficiency is different when it is measured by different institutions. Their standard about total efficiency are various. Total mechanical efficiency is combined with three aspects: total value of transmission efficiency, engine efficiency and differential efficiency. There is no agreed value for transmission efficiency and differential efficiency. The differential efficiency varies from 75% to 95% through literature review (Division, Quality & Agency 2010). It is hard to get an agreed differential and transmission efficiency. In addition, engine efficiency varies from different engine type, engine size and cylinders numbers. To solve the problem, energy efficiency is introduced to describe total mechanical effectiveness in this case study. According to U.S. Department of energy, gasoline energy, which is used for driving a vehicle on the road, is between 14%- 30% (Picture.1) (U.S. department of energy 2015). The power consumption is shown at below (Figure 6.7). The mechanical efficiency of a gasoline vehicle ranges from 14% to 30%. In this research, the total mechanical efficiency of petrol vehicles is 20% considering the greater average vehicle age (12 years) and larger engine size in Australia.

In contrast, the efficiency of a diesel engine is 8% - 15% on average higher than a petrol engine. In this case study, the total mechanical efficiency will be 28% , which is 8% more than a petrol engine. Heavy duty vehicles always have better performance on engine efficiency. It is assumed that heavy vehicles will have the highest mechanical efficiency of 30%.

To get accurate total mechanical efficiency value, it is important to use regional energy efficiency values and vehicle information. The Australian Bureau of Statistics has data on vehicles. Cooperation and coordination are recommended to get the regional average vehicle information from the local road agency.

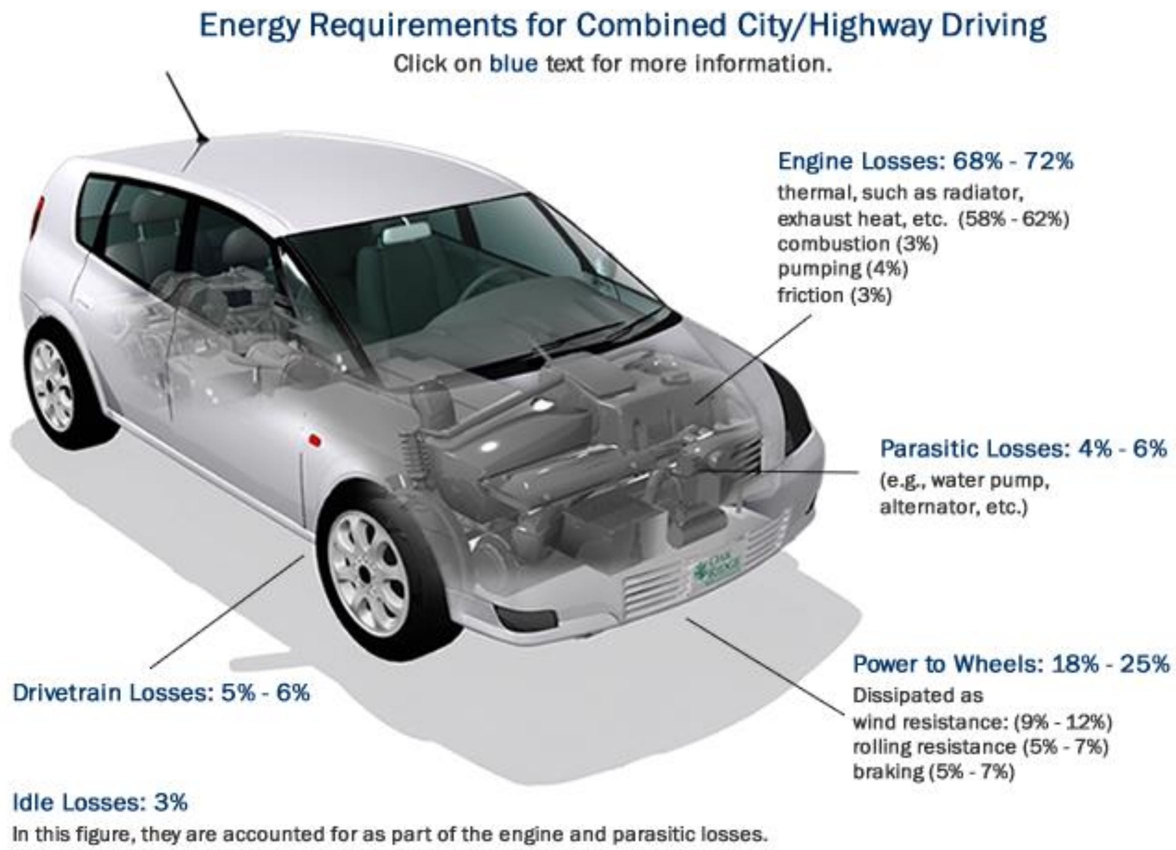


Figure 6.7 Energy consumption and efficiency(U.S. department of energy 2015)

Another difference between different vehicles is the coefficient of rolling resistance. The values will change for different road surfaces and vehicle types. The field work shows that the main road surface types around Kapernicks Bridge are concrete and asphalt. For light vehicles, the coefficients of rolling resistance on concrete and asphalt are 0.013 and 0.03 respectively. The coefficient for a heavy duty vehicle is only 0.008 on average. Currently, there is a new low-rolling resistance tyre. Low rolling resistance tyres can achieve low value for both light and heavy-duty vehicles, but no evidence shows that low resistance tyres have taken the tyre markets. Therefore, coefficients from special tyres will not be considered in this case study.

In order to estimate insurance costs accurately, the weighted average value is significant. Insurance costs will be different due to vehicles' purchase price, vehicle type and vehicle purpose. In this case study, vehicle number and constitution information are a constraint that is further grouped by purchase price and vehicle purpose. The insurance and maintenance costs are the main reasons that can lead to cost differences between light vehicles and heavy-duty vehicles in this case study. The registration, maintenance and insurance costs of small vehicles are around 3000-4000 AUD at 2011 price level (Commbank 2012). By comparison, the costs for heavy-duty vehicles are between 17000 and 40000 due to different axels and carrying capacity (Freight Metrics 2015).

Another two parameters which will affect fuel consumption are frontal areas and coefficient of air drag. Sedan, UTE, SUV, light commercial vehicles and heavy-duty vehicles due to their distinguish dimensions and exterior. Also, the same vehicle type will also have different air drag coefficients for their different designs in different manufacture years. In this case study, popular vehicle models will be chosen, and extreme design value will be ignored. For private vehicles, models of popular brands, for example, Toyota, Honda, Holden, etc., are selected to estimate common frontal areas and drag coefficients. Their dimensions and tech specs can be derived from their detailed technique specs. For heavy-duty vehicles, research showed that the average frontal areas are 10 m^2 (Giannelli et al. 2005). The air drag coefficients are very different regarding heavy-duty vehicles with new technology to reduce air drag. The lowest value could even reach 0.45, which is close to large SUV level (Wood & Bauer 2003). However, there is no popularizing rate in the percentage of heavy vehicles that have been applied with this new technology. Therefore, general data will be chosen for the air drag coefficient.

Some problems can affect the accuracy of this case study. The problem is that the traffic number is small in this case study. Therefore, vehicles cannot be separated into particular groups by their characteristics. Another problem associated with the small traffic number is that information from the small bridge is not as detailed as the information from a bridge that is located in a vital position with a great traffic volume. For example, the West gate bridge, which is located in Melbourne, has more detailed traffic information than the Kapernicks bridge. Another problem is that some values cannot be derived from Australian institutions or regional databases. That circumstance may affect the accuracy of this estimation. The Vehicle operating costs are presented below:

Table 6.16 Vehicle operating costs

Vehicle type	Fuel type	Operating expenses (AUD/km)
Private vehicles	Petrol	0.7389
Private vehicles	Diesel	0.7009
Light commercial	Petrol	0.7039
Light commercial	Diesel	0.6721
Heavy-duty vehicles	Diesel	2.014

For private vehicles, RACV provides a reasonable operating cost range, from 0.59 AUD/ Km to 1.08 AUD/ Km (RACV 2015). The results include information about small, medium, and large private vehicles in the Australian market. Operating costs results for private vehicle, which are 0.7389 AUD/ Km and 0.7009 AUD/ Km, are close to medium sedan and pick-up operating expenses. Therefore, the operating costs for private vehicles should be reasonable.

For light commercial vehicles, the operating costs are slightly lower than those for private vehicles. The main reason could be that the maintenance cost is only 0.085 AUD/ Km. This data should be taken into consideration because the maintenance cost of private vehicles is

0.1984 AUD/ Km. However, according to RACV, the operating results were lower than they were for people mover vehicles with 0.78-1 AUD/ km at 2014 price level (RACV 2014). The results should be reasonable if the maintenance cost is close to that of private vehicles.

For heavy duty vehicles, the operating expenses range from 1.7 AUD/ Km to 2.7 AUD /Km. According to the Australian Bureau of Statistics, 99.5% of heavy-duty vehicles use a diesel engine. In this research, it is assumed that all heavy-duty vehicles are equipped with a diesel engine. Heavy vehicles have the highest vehicle operating cost of 2.014 AUD/ km. Heavy vehicles have higher tyre prices, insurance costs, purchase prices, maintenance costs, and registration fees. The results are close to the operating cost calculator.

6.4 Debris disposal costs

To estimate debris disposal costs, the first step is to identify disposal methods for different types of debris. Recycling debris can be transported to sorting systems and recycled. Putrescible wastes would be carried to dump sites and landfilled. In this case study, all debris, which is construction wastes and putrescible wastes, would be carried to dump sites and disposed together. Recycling and putrescible debris are not separated and disposed separately. In order to easily calculate landfill costs, another three aspects will be considered in this case study:

(1) The size of the dump site. Larger dump sites will have lower field purchase costs and management fees. In one word, the larger the dump site is, the lower the disposal costs will be.

(2) The location of the dump site. Location can impact disposal costs. Dump sites in rural areas will have lower land prices and fewer impacts on the surrounding population. Also, dump locations in the countryside will have lower impacts on surroundings and the environment.

(3) The control condition of the dump site. There are significant differences between dump sites with good and poor control conditions. Debris in good condition dump sites will have fewer impacts on the environment. The indirect intangible costs to pay for environment credit will be lower than that for a dump site with a poor control condition. In this case study, the small dump sites were located in rural areas with a reasonable control condition. Refer to Table 5.4, the costs for debris disposal are as below:

For the debris disposal costs: the costs are around 100 AUD/Tonne

6.5 GIS map development and surrounding road networks

This map will include two types of maps: road maps and satellite maps. Roadmaps will focus on bridge and the surrounding road networks. Satellite maps will contain information about residents and industry. Both these maps are necessary to estimate the economic impacts of bridge damage and road networks.

(1) In the traffic routes, the first stage is to add basic information, including closed cities, main services location, main roads and networks and road types in regional areas.

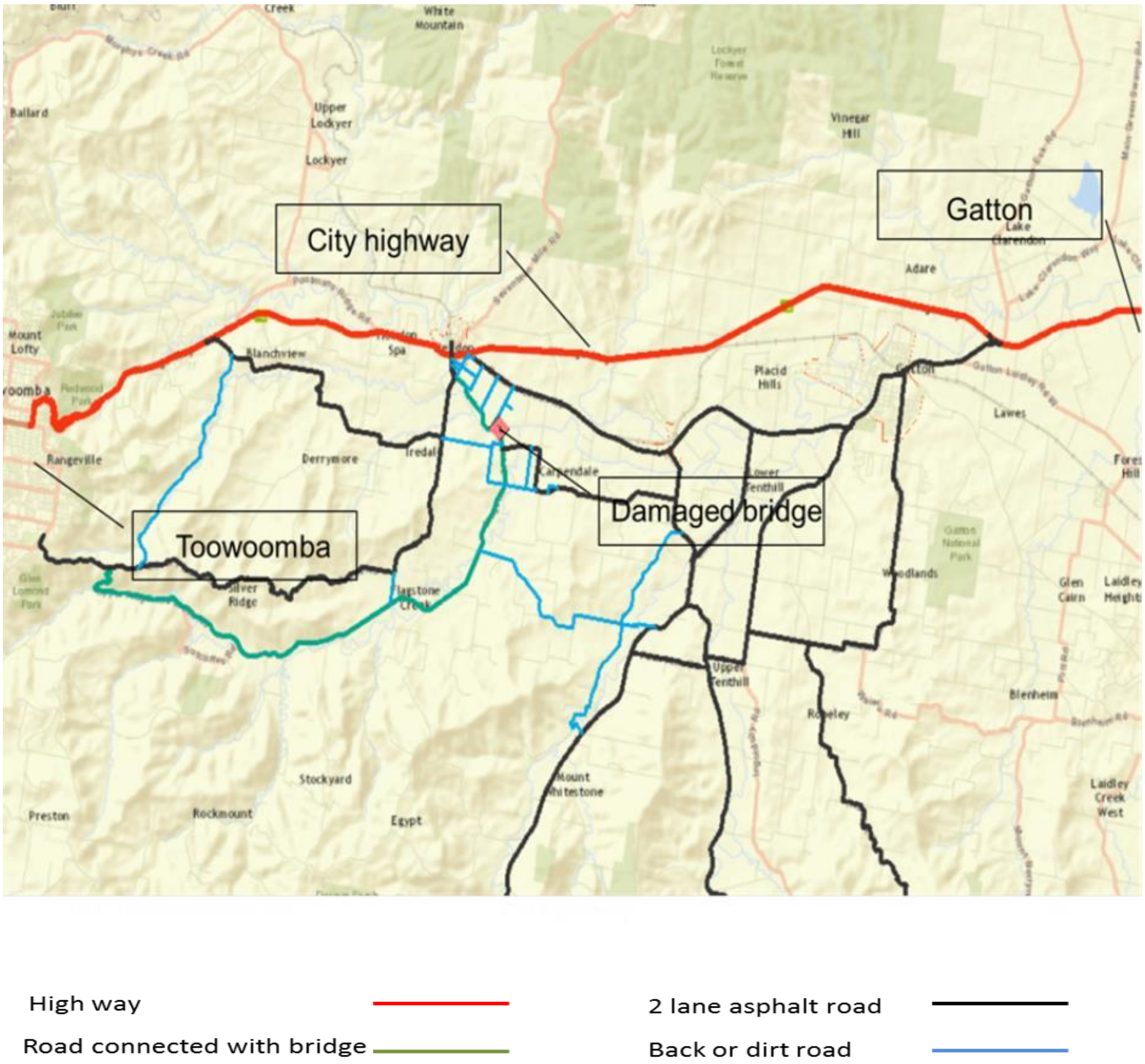


Figure 6.8 General condition of road maps

The first map includes the location of the damaged bridge and surrounding road networks. There are three types of roads that are marked by different colours: highway, two-lane asphalt road and back road. There are one big city and one small town in this map: Toowoomba and Gatton. They are the places that will provide the main services to the surroundings. This damaged bridge is a faster way to travel to the highway which connects Toowoomba and Gatton. The main impact of bridge damage is its effect on the travel between the highway (Warrego Hwy) and the other sides of the river (Lockyer Creek). The purposes of travellers can be separated into two aspects: On the one aspect, there are mainly farms, small businesses and industries on the southern bank. For production aspects, small businesses, industries and farms use this bridge to keep accessibility to the northern part of the Lockyer Creek. In this case, around 35 percent of vehicles work for the exchange of products and production materials. On the other aspect, there will be different impacts on residents who live on different sides of the river. Inhabitants who live on the southern bank of the river rely on this road to get necessary services, such as fuel, food, and medical services. Inhabitants who live on the northern side usually use this bridge for commuting and freight.

(2) In this step:

(a) Identify the road status of the damaged bridge.

(b) Compare detour alternative routes.

(c) Analyse traffic distribution to the alternative road after bridge damage.

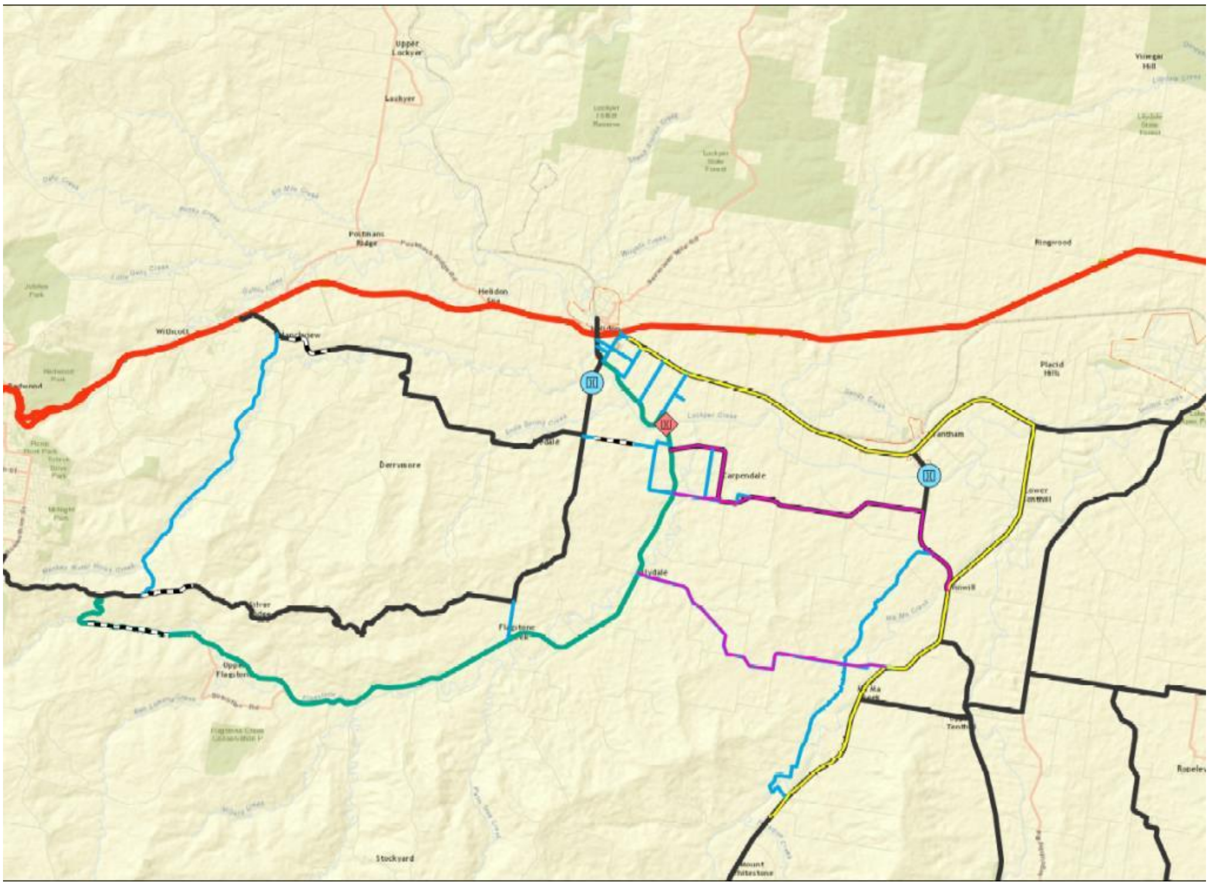


Figure 6.9 Different road types and regional traffic information

Roadmaps and regional traffic information allow for the comparison of traffic flows. Also, they can be used to identify the importance of a bridge in local transportation. In this case study, the Kapernicks Bridge is a part of Flagstone Creek Rd. This road belongs to the Lockyer Valley Regional Council. It can provide faster and more convenient traveling to Warrego Hwy. In this road system, there are two other bridges that are close to the damaged bridge and can divert traffic flow. One of the two bridges has a lower carrying capacity, and not all connected roads are as good as the Kapernicks bridge. The other one is not as convenient to residents. The condition of the detour road is not as good as that of the Kapernicks bridge which makes the Kapernicks Bridge important to bridge users and local businesses. Kapernicks bridge would take the main traffic flow.

This step will discuss alternative roads. After bridge damage, the traffic flow of the Kapernicks Bridge will be diverted to alternative routes. During this period, alternative roads will maintain accessibility for the local community. Travellers can use this bridge to get in and out of the southern side of the bridge. One or two alternate roads will take more traffic volume. The average extra traveling distance and time should use the weight value that is the rate of diverting flow in different alternate routes. In this case, it is an extreme condition that only one alternate road was available after the 2011 flood event. Two reasons may lead to this situation. First, different damages are generated to different sections of alternative roads and bridges after the flood events. Because of this, some potential alternate routes are not available. Secondly, some alternate roads do not have good road conditions, which makes travellers have less willingness to travel on these paths. In this circumstance, only one road that is marked by a yellow line which is mostly used by residents. Almost all of the residents use this route as an alternate road. For travellers, two roads can help bridge users to travel from the main road to the alternate road. A Pink colour line marks these two branch roads.

(3) Use satellite map to identify resident density and impacted industries.

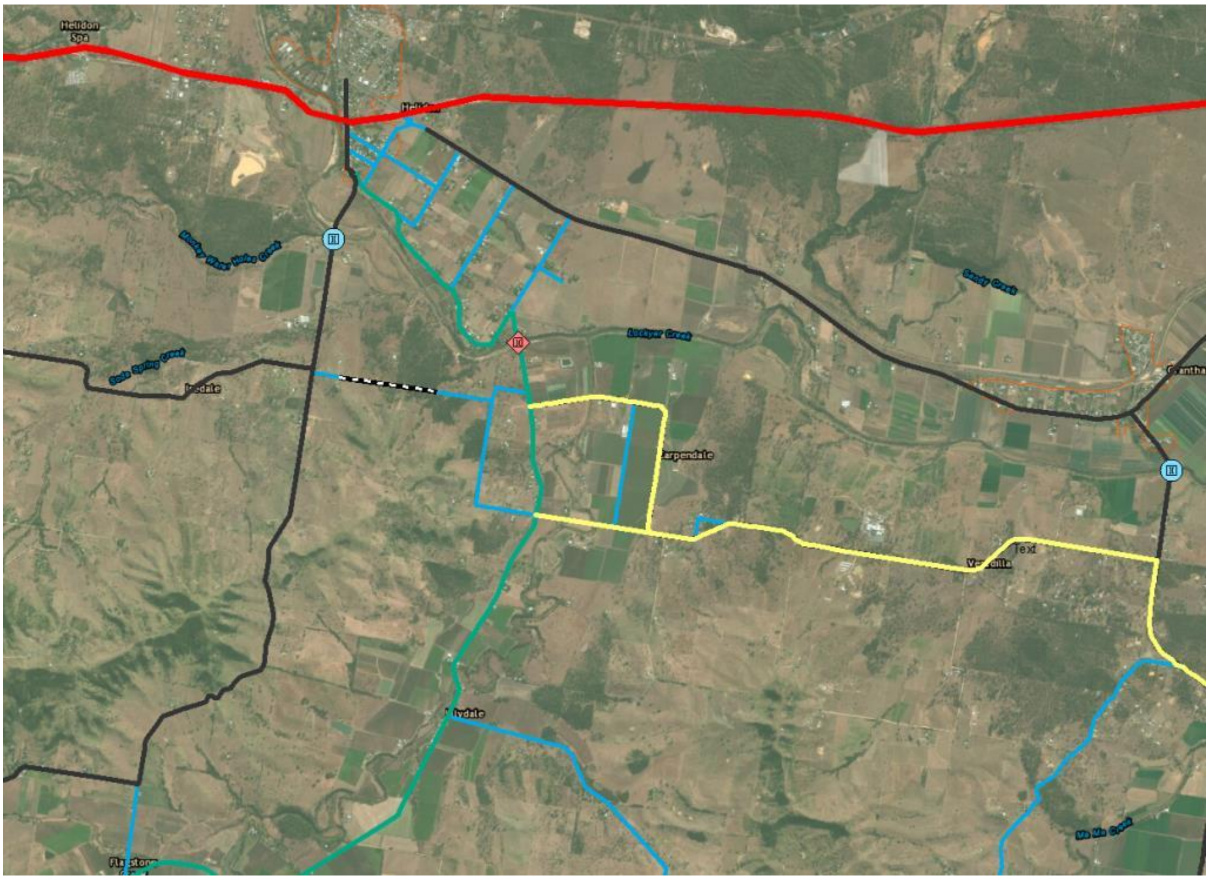


Figure 6.10 The satellite maps

This satellite map is used to identify the distribution of residents and industries. In this case, farms and industries are scattered along this road. The density of residents and industries is small in this area. In Comparison with high population density areas, there will be less transportation demand. Also, this bridge and route are mainly for local travellers. Kapernicks Bridge is not part of any important transportation towns that connects important town and cities. It is used mainly for satisfying local traffic. Therefore, the traffic demand and volume will be steady before and after bridge damage. There will be less traffic pressure on the local transportation system. Traffic jam is less likely to take place when traffic flow is diverted from the damaged bridge.

(4) Measure traveling distance and traveling time

To measure traveling distance and traveling time, Google Maps are introduced to help calculate extra traveling distance and traveling time in this case.

(a) Choose multiple pairs of departure and destination points on both sides of the bridge.

(b) These routes will include as many directions as can be possible.

(c) The routes should include the main traveling destinations and services.

The next step is to measure traveling distance and traveling time that via alternative roads:

(a) Apply the same departure and destination points to measure detour distances.

(b) Measure the marginal point for each alternative road.

(c) Compare traveling distance and traveling time, and record points with increasing either the traveling time or traveling distance.

In this case, the traffic routine is very simple. Toowoomba can include the majority of destinations for medical services, shopping, school, and fuel. The regional economic report describes Toowoomba as the highly attractive and close destination (The Stafford Group 2013):

"The proximity of the Lockyer Valley to major population centres in Ipswich City, Toowoomba and Brisbane makes the Lockyer Valley highly accessible as an attractive day trip and short stay destination. Whilst the closeness of the Lockyer Valley to these major population centres (Ipswich City is approximately 30 minutes away, Toowoomba approximately 20 minutes away and Brisbane approximately 1+ hour) is a plus in being able to offer easy access for a number of consumer markets. "

Compared with Toowoomba, Gatton can only provide limited services that cannot satisfy the majority of residents' demands. Traffic from Toowoomba would like to use the bridge to access farms and industries. To summrize the difference between original route and alternate route, the extra travel distance and extra travel time are presented: (1) Bridge users needed to travel extra eighteen to twenty-four kilometres to access to Toowoomba. (2) For the majority of the bridge users, it will take around an extra fifteen to twenty-five minutes to Toowoomba.

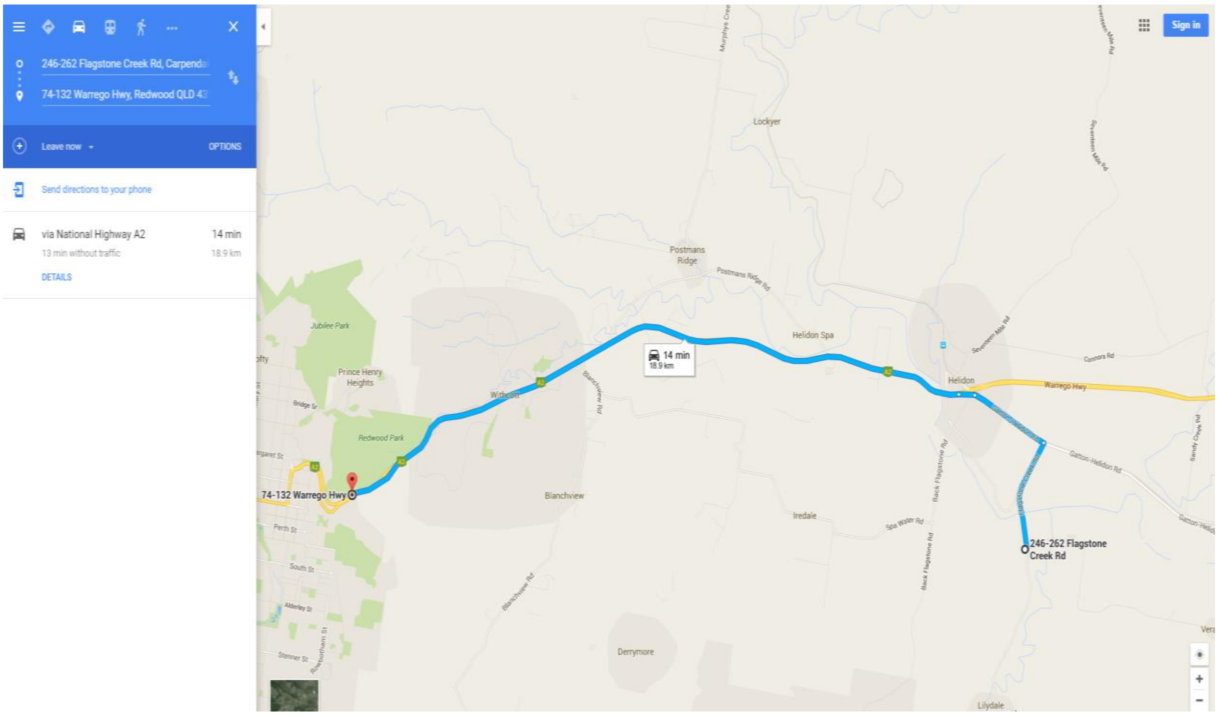


Figure 6.11 Traveling distance and time before bridge closure

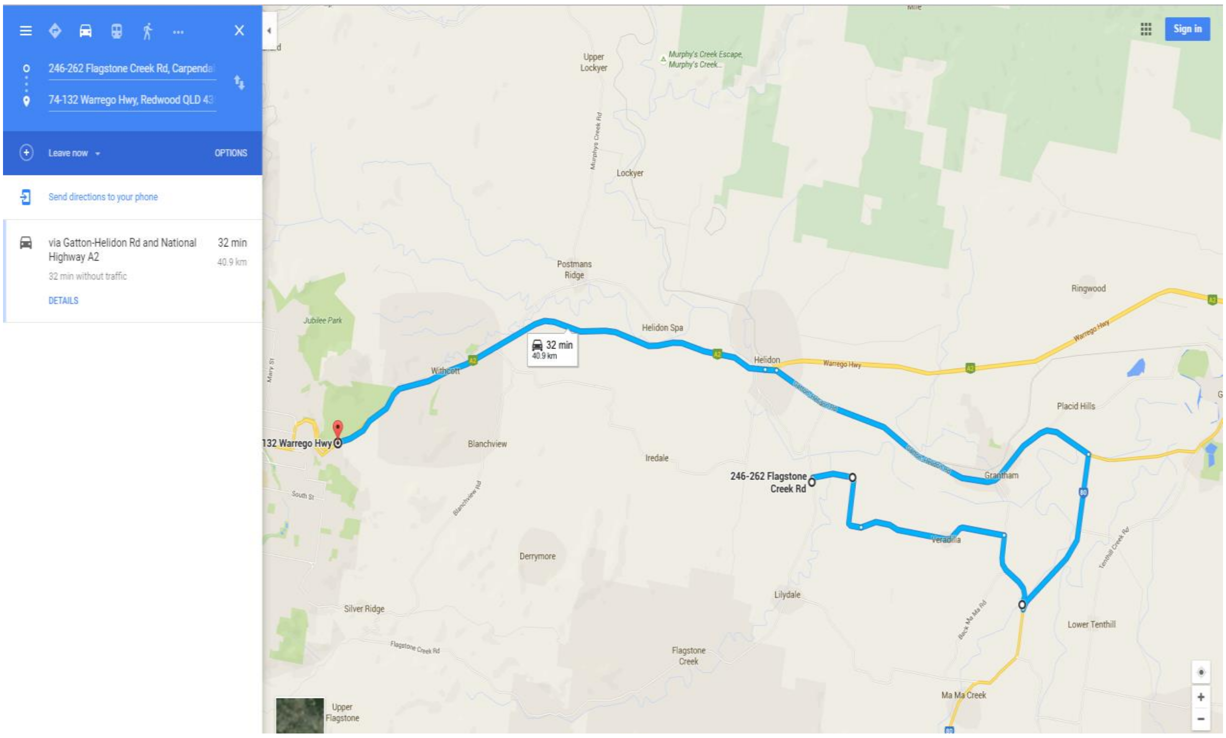


Figure 6.12 Traveling distance and time by alternate road

(5) Identifying the traffic-impacted region.

After comparing the increasing traveling time and traveling distance, the traffic-impacted region can be identified. In this case, traffic problems happen to vehicles that would like to travel from the highway to Flagstone Creek Road. Travellers who travel between Flagstone Creek Road and the highway will be impacted. This means that travellers who travel between Toowoomba and the suburbs (Iredale, Veradilla and Flagstone Creek) would be affected. There are two marginal points that are shown below. These two marginal points have similar traveling time (the difference between traveling distance is less than 4km).

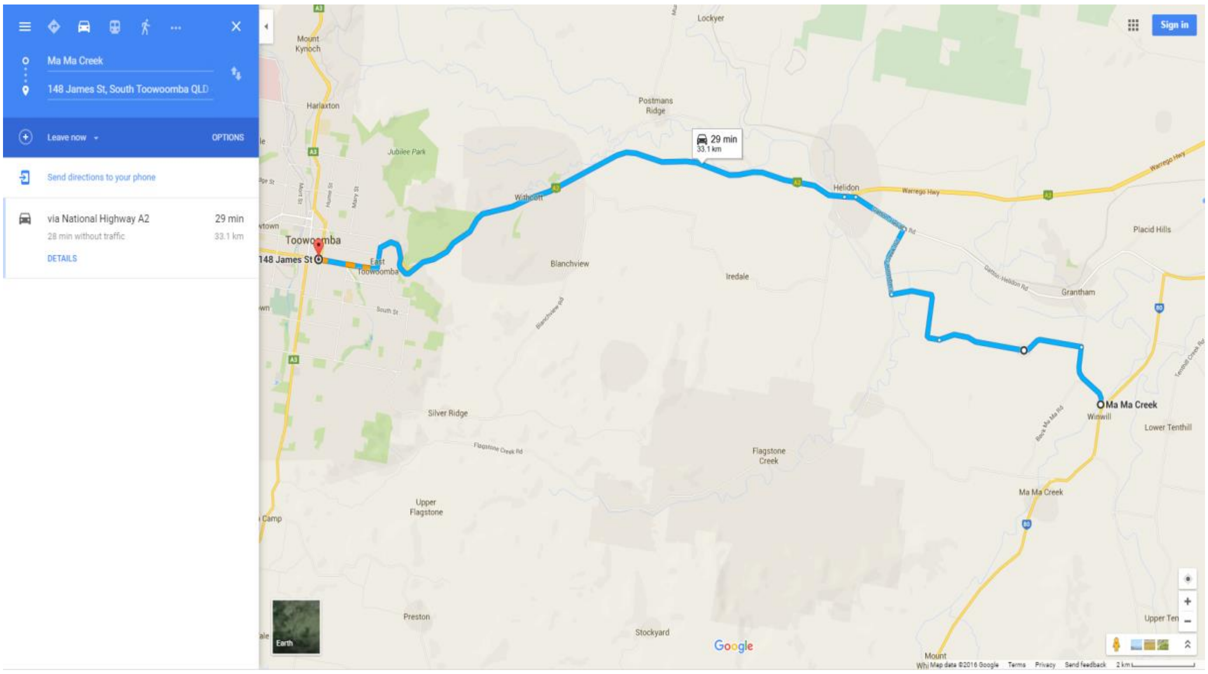


Figure 6.13 First marginal point routine use bridge

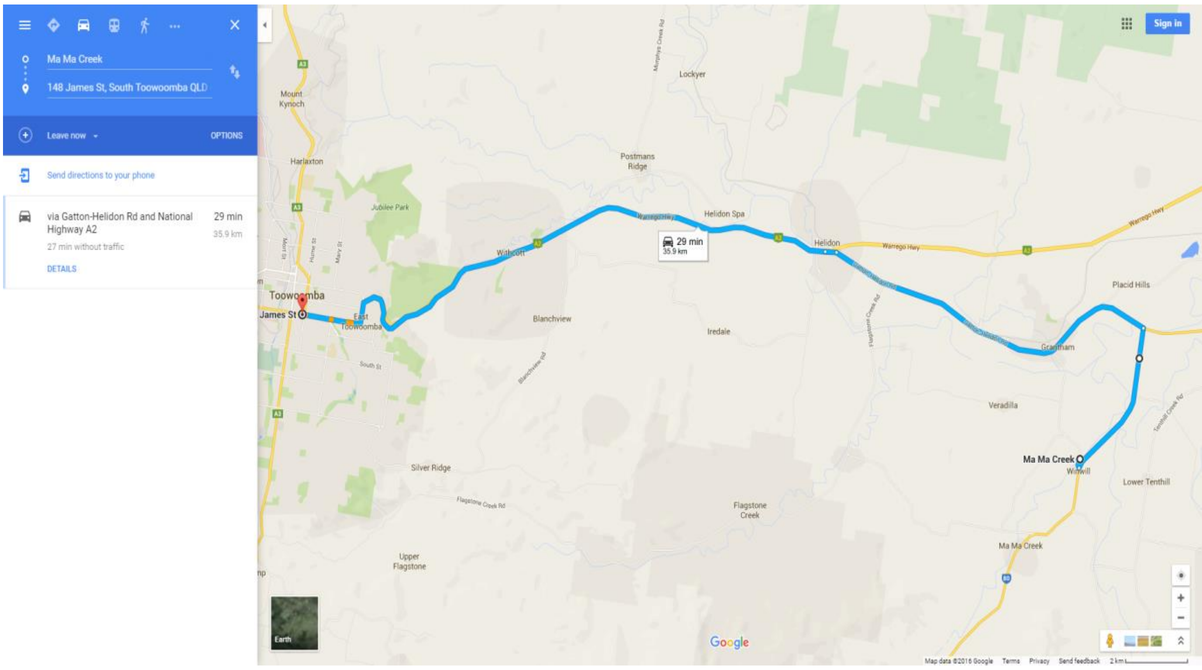


Figure 6.14 First marginal point routine with alternate road

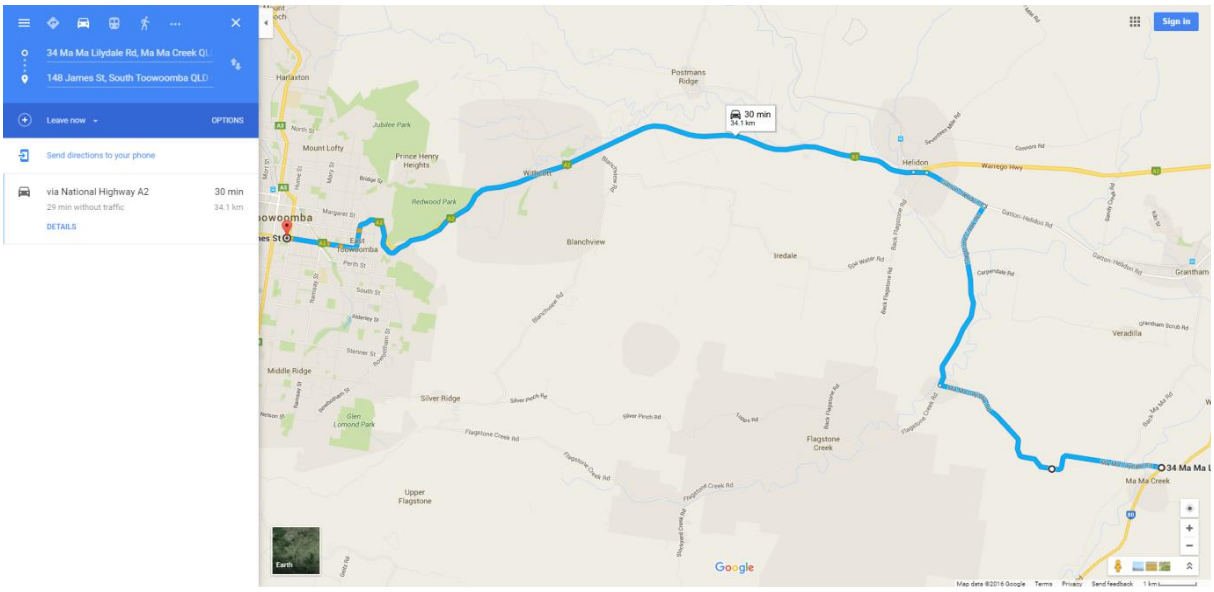


Figure 6.15 Second marginal point routine with bridge

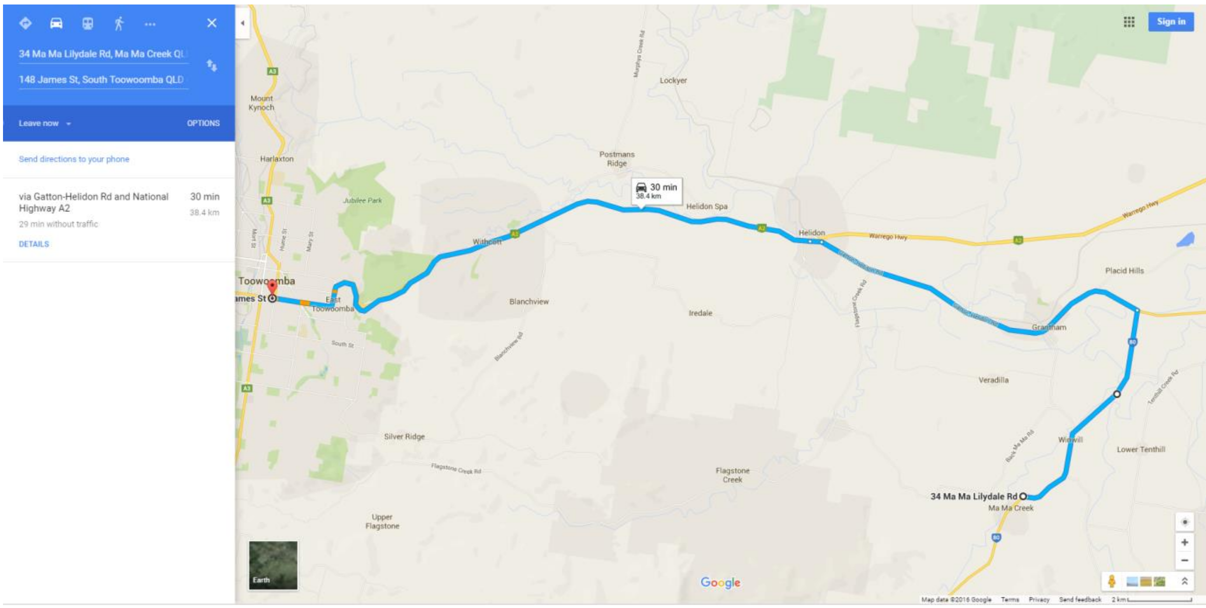


Figure 6.16 Second marginal point routine with alternate road

This comparison shows that Gatton-Clifton Rd (marked by the yellow line) can be simply used to mark the impacted traffic region. The majority of the impacted region is located on the left side of Gatton-Clifton Road.

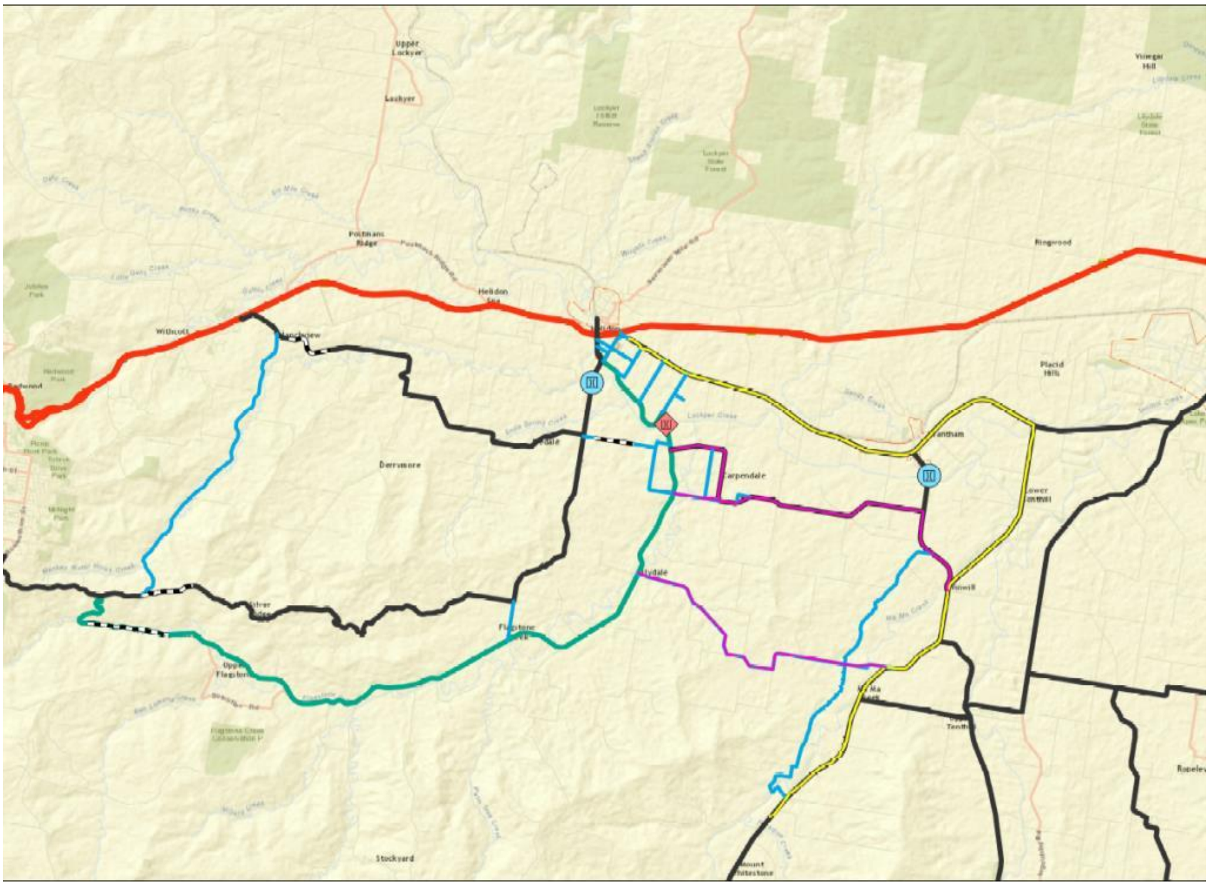


Figure 6.17 Sketch map of traffic affected region

6.6 Economic impacts of damaged bridge

6.6.1 Direct economic costs

6.6.1.1 Debris cleaning costs

In this part, three types of costs will be estimated, including debris collection, debris transportation, and debris disposal. The first step in this part is to estimate debris quantities. Debris quantities can be estimated during bridge inspection. However, debris quantities records are not available. Therefore, information on debris quantities can only be collected from fieldwork and post-disaster images. The images show that fewer branches,and less sand and soil were built up on the superstructure and the upstream side of the bridge. Related information that was collected from local council is that one or two trucks of debris and construction wastes are transported to dump sites together. According to Australian vehicle classification, the medium heavy truck would have a 9-tonne mass loading. Therefore, the maximum mass of debris would be between 9 and 18 tonnes. It is assumed that the debris created during bridge recovery was 13.5 Tonnes in this case. To estimate the debris clearance costs, estimation follows the rules:

$$D_{debris\ cleaning} = D_{collection} + D_{transportation} + D_{disposal} \tag{13}$$

(1) Debris collection costs will introduce costs for site preparation in Rawlinson's Australian construction handbook. The costs vary from 0.5 AUD to 2 AUD per m^2 due to different debris types. In this case, the collection costs will use an average price level (1.25 AUD).

$$D_{collection} = Q_{Debris} \times E_{clean} \tag{15}$$

The working area will include bridge surface, bridge bottom, and some extra areas around the approach roads. The extra areas are used to provide a proper working condition, which is always related to the bridge dimensions, damaged scales and construction technology. For this bridge, the cleaning scale is bridge areas of 100 m^2 on each side of this bridge and 120 m^2 on the upstream side of the bridge. The cost for debris collection is around 902.95 AUD.

For an estimation of the debris transportation costs, it is assumed that the debris will be delivered from both sides of the bridge separately. In this case, the debris will be transported to the Gottan dump sites, which are located around 16.6 km from the north side and 21 km from the south shore (16 minutes and 24 minutes respectively). In this case, the trucks will depart from the two sides of the bridge and the transportation work will be finished within half a day. The traveling distance would be 54.2 km. According to the Queensland salary scale, the salary of a heavy duty vehicle is 19.63-30.89. The average wage is 25 AUD. The transportation costs will be:

$$D_{transportation} = \sum[(Q_{Debris}/M_{trip}) \times C_{vehicle} \times S_{dump}] \tag{16}$$

The cost is around 110 AUD. Driver salary is around 100 AUD. Total transportation cost is around 210 AUD

Debris was transported to dump sites and landfilled after the 2011 flood event. Costs for mixed debris would be:

$$\mathrm{D_{disposal}} = \mathrm{Q_{Debris}} \times \mathrm{C_{disposal}} \tag{17}$$

The costs would be 1350 AUD

In this case, debris clearance would cost 2462.96 AUD. It is around 2500 AUD.

6.6.1.2 Bridge recovery costs

This section would mainly discuss the steel bracing of the girder. Currently, there are inspection reports, repair plans and bracing drawings of bridge girders. Therefore, girder recovery will be an example of estimating costs for bridge recovery. To make reparation of a damaged bridge, repair methods and construction technology would be different, depending on bridge construction. Some cost items cannot be associated with Rawlinson's construction handbook. Therefore, it is better to estimate quantities of repair work and estimate total costs by consultants. This research would be a summary of the quantities that happened during the bridge repair procedure.

First of all, cracks on the girder will be repaired. An epoxy (SIKADUR 52) injection would be applied to repair large cracks. Four major cracks and their branch cracks on the girder will be repaired. Four steps would be taken during this period:

(1) Crack surface preparation and cleaning requirement

(2) Sealing of cracks for epoxy injection

(3) Epoxy injection

(4) Cleaning after epoxy injection

After epoxy injection, steel bracing would be applied to the girders to improve the strength and stability of the bridge. Steel members would be installed on girder4 in span2 and span3. During this period, around 70 strengthening arrangements and nine groups of steel bracing members would be fitted. Basic installation procedures are:

(1) Drill 40 mm holes through the deck for vertical bars.

(2) Break out pockets for top anchorage to a depth of 55mm.

(3) Install a bearing plate on a bed of SIKADUR42.

(4) Scabble a soffit of the beam at anchor locations.

(5) Lower bars and lift bottom anchorage on bed of SIKADUR 30.

(6) Tension bars simultaneously to 82kn on both sides.

(7) Fill the infill pocket with high strength epoxy mortar (SIKADUR 42).

(8) Install a grease cap over the lower anchorage.

(9) Install new horizontal struts.

At present, the Rawlinsons Australian Construction Handbook cannot provide the costs of Epoxy and drill properly. Therefore, the estimation results mainly rely on consultant. In addition, the local council focuses on the total costs of repairing a damaged bridge. The total repair costs of forty-two damaged bridges in the 2011 flood event were recorded. The costs of single structure component are not available.

6.6.2 Direct intangible losses

Two types of intangible value would be discussed in this part: the intangible value of the historical building and the psychological impact on bridge users. For the psychological impacts on bridge users, this case would like to collect data and resources that could minimize the impacts of bridge damage.

In this case, the Kapernicks bridge is not a historic building. It was built in 1981 to support the development of regional farms and the agricultural industry. It is an important transport routine to the local community and makes contributions to the local community. However, this bridge is not considered a historic bridge.

Regarding psychological impacts on bridge users, the consequences are hard to predict. Bridge users have to face detours, increased traveling time, additional travel distance, and not ideal road condition if they do not cancel their daily trips. There would be emotion change of bridge users. To minimize possible adverse impacts, the local council will introduce different measures to improve the traveling experience. At this stage, different efforts and resources will be used. For example, the Lockyer Valley council get damaged bridge a quick repair to allow one side of the bridge to open to small vehicles. However, it is hard to determine whether these measures are effective or not. This case study intends to record efforts of the local council to provide fodder for further research on exploring psychological impacts on bridge users. Public resources invested in Kapernicks bridges included:

(1) After bridge damage, there was an emergency repair. The damaged bridge body was strutted by temporary supporters around three weeks after flood events. Also, steel plates were used to connect the broken bridge for temporary use. Steel supporters and plates were used for one year until the bridge opened to the public.

(2) Extra temporary traffic lights were used on two sides of the bridge when one side of this bridge was open to the public. Guiding designs and road signs were used to improve accessibility and detours for bridge users.

(3) After 2010 flood event, some locations were disconnected with the outside due to problems caused by road infrastructure damage. Therefore, extra communication equipment was used in this area to help residents to connect with each other. The local council organised a set of CB radios and couples of repeater stations. Optus handed out satellite phones, and Telstra built underground cabling after 2011. In 2011 flood events, some flood affected areas

were without phones for six weeks. Emergency radio made a big difference in that case. A large number of social resources were invested to improve communication after 2011. By doing so, 2013 flood events were more manageable than 2011 flood event, even though the physical impact of 2013 flood was worse than that of the 2011 flood. Currently, there are still households that are not covered by mobile phone towers as both Telstra and Optus coverage have gaps. More resources would be invested in flood-venerable areas.

(4) Staff should receive and respond to advice, inquiries, and complaints from bridge users. After flood events, there is a lot of things that are related to disaster relief, restoration, and official documents. The local council set temporary consultant to solve travel problems of resident. In this part, some local inhabitants felt good, while some complained that consultant could not solve their problem.

After flood events, total disconnected time of the bridge lasted around two weeks for emergency repair. After two weeks, this bridge was open one side to small vehicles. It took around one year to finish the whole bridge restoration and be fully open to the public. During this period, the majority of bridge users had to either use one side of the bridge or chose other routes.

In conclusion, there would be displeasure and anxiety when stakeholders of the bridge noticed they might lose connection to the other sides of bridge. The local communities appreciated the efforts that are made by the local council. However, not all the efforts could satisfy the local community. The local council needs to make more efforts to guide travel and detour when bridge are closed or partly closed.

6.6.3 Indirect tangible losses

$$\mathrm{IDC_{tangible}} = \sum(\,\mathrm{C_{detour}}, \mathrm{C_{production\ capacity}}, \mathrm{C_{time}}) \qquad (20)$$

In this part, three types of losses will be discussed. First of all, the extra detouring distance will increase the expenditures of bridge users on traveling. Secondly, products of traveling through disaster-affected regions would impact the productive capacity of local industries. Thirdly, there are opportunity costs for the extra time that is spent on detouring.

6.6.3.1 Detour costs

In this case, vehicle operating costs depend on detour distance. Detours, in this case, can be separated into two periods:

(1) During bridge closure, all vehicles have to travel around the damaged bridge. One lane is opened to the public around 4-5 weeks after flood events. Bridge stakeholders would travel around 22 km on average.

(2) One side of bridge is open for small vehicles. At this stage, heavy vehicles have to detour and small vehicles can use this bridge. In different cases, vehicles would like to detour to avoid heavy traffic. Under this circumstance, the rate of vehicles that choose to use bridges should be measured. Regarding Kapernicks Bridge, due to the low traffic, there was less likely to have traffic congestion. Therefore, the majority of light vehicles would use the bridge instead of long-distance detouring. However, traffic flow was still impacted in this procedure. According to the local council, it took ten more minutes to cross the bridge on average during construction.

In terms of extra traveling distance, two periods should be calculated separately: during bridge closure periods, vehicle operating costs would include all types of vehicles. After one side of the bridge was open for small vehicles, it is assumed that light vehicles would use the bridge, and only heavy vehicles would detour.

$$C_{detour} = S \times C_{vehicle} \times N \times t \tag{21}$$

To summarize the traffic volume of vehicles:

Table 6.17 Traffic constitutions

Vehicle	Rates	Patrol (%)	Diesel (%)
Sedan	60%	80.6	19.4
Light Commercial	13.5%	37.7	62.3 (55.7)
Heavy vehicles	26.5%	0.5	99.5

According to the local council, the average number of cars is 729 per day. Heavy vehicles count for 26.5% of all vehicles. There are not clear statistics to distinguish light commercial vehicles and sedans. In order to estimate the number of light commercial vehicles and sedans, vehicle constitution in Queensland refers to Australian Bureau statistics. Also, Australian Bureau statistics provides data about different fuel types. In Australia, gas and other fuels have very few markets, which is less than 1%. To be easily calculated, other fuel types are included in diesel. Frankly, one character of this bridge is the number of heavy vehicles larger than the average condition in Queensland. One of the main reasons is that the majority of stakeholders in this region are farms and industries. Heavy vehicles are essential for product delivery. In addition, it is convenient for farmers and small industries to hold light commercial vehicles.

On average, the mean extra traveling distance is around 22 km. The additional expenditures for different types vehicles during four-week bridge closure:

(1) For heavy vehicles: 239440.432AUD

(2) For private petrol vehicles: 160464.956 AUD

(3) For private diesel vehicles: 36636.778 AUD

(4) For light commercial petrol vehicle: 16087.714 AUD

(5) For light commercial diesel vehicles: 25384.288 AUD

From this estimation, heavy vehicles would cost a significant amount of money when they have to detour. That will be considerably increase costs for product delivery.

When the bridge opened on one side to the public, it is assumed that almost all private vehicles and light commercial vehicles will use the bridge due to traffic conditions and long detour distance and detour time. In this circumstance, only heavy vehicles would create detour costs:

For heavy vehicles in the whole year (it is assumed to be 365 days), the costs are around 3121277.06 AUD.

6.6.3.2 Productive capacity

To estimate impacts on the productive capacity of regional industries, different products and materials that move in and out to support the local industry before and after bridge damage is the primary index. Without sufficient production materials and resources, productive capacity will decrease. Also, farms and industries need to get the extra resource to recover from disaster events. For industries, recovery resource would impact short-term production. For local farms, delay of recovery may impact the whole year agricultural production. The Lockyer Valley is the most significant agricultural production region within South East Queensland (SEQ). The Lockyer Valley is positioned on the Western Growth Corridor of Brisbane and within easy distance and access to the Port of Brisbane and the international airports at Brisbane as well as the Gold Coast(The Stafford Group 2013). The bridge damage and its decreasing accessibility could impact regional agricultural economy.

Lack of resources would lead to decreases in production capacity and gross production:

$$\mathrm{C}_{\text{production capacity}} = \alpha_{\max}(1 - \Delta\,)\mathrm{P}^{\text{ini}} \tag{22}$$

Where, P^{ini} = the pre-event production capacity, $\alpha_{\max}$ = the maximum production capacity, Δ= loss of production capacity

$$\Delta = \mathrm{Max}\left(\frac{S_r - S_s}{S_r}\right) \quad (23)$$

Where, S_r=Resource needed for daily production, S_s= resource can be supplied by delivery after bridge damage.

In production procedure, sufficient resources would be substantial for production. It is important to maintain stocks on time so as to maintain proper daily productive capacity. In this procedure, the resource could be separated into different types: power, water and materials that could rely on bridges and transportation. To collect data for the production resources that were transported via the bridge and received after bridge closure could help estimate productive capacity as it is impacted by resource limit. This model would compare different resources that flow in and out of the traffic-affected region to predict impacts. This estimation needs to collect three types of critical data:

(1) A number of services, materials, and supplies that support local farms and industries should be collected before disaster events. As the main thoroughfare to both sides of the river, the transportation of products relies on the bridge. In this model, it is assumed that the stock of productive resources is the main factor that would constrain productive capacity. Daily, weekly and monthly provisions are important data to measure the daily consumption of production procedure. Different types of resources should be calculated as a base to maintain productive capacity.

(2) Information about recovery resources that are needed by industries and farms should be collected. Different damage states can be observed after disasters. Most of the time, damage relies on resources, technic support and machines that are outside of disaster-impacted regions. Damaged bridge and road infrastructure would create barriers to timely recovery assistance after disasters. This record would collect the regional demand of resource that rely on this bridge to access the disaster-impacted region.

(3) Insufficient services, materials and supplies would be collected. Capital goods that access traffic-impacted region should be recorded. During the bridge closure and repair period, products can access to the traffic-affected region via the alternate road. In this circumstance, delay and productive insufficiency of the capital products should be observed and recorded.

There are meat industries and farms that are located on the southern bank of the river and that rely on the damaged bridge. To predict post-disaster productive capacity, data is needed as follows:

(1) In terms of local businesses, the majority of local industries are agricultural processing industries. These industries rely on materials, workers, machines and power and water supplies. Changes in inputs, for example, the supply of livestock, power and water before and after the disaster, are important indexes to measure productive capacity and industry output change. After the 2011 flood event, some companies provided transporation helps to their employees that could not reach to work to resume production. Also, the local community provided help to resume local power and the internet networks after the flood events. From the interview, power and network were necessary for resuming business after flood events. In this case, some statistics were not in detailed:

(a) Power recovery is impacted by traffic conditions, and recovery time varies from house to house. Both power and network recovery schedules should be recorded. Also, recovery delays due to bridge closures and traffic problems should be noticed. (b) farm and industries' daily consumptions that are used to maintain productive capacity should be collected. An input matrix is needed to summarize regional resource consumption. (c) Available resource and inputs that can be provided after bridge closure should be recorded. After flood events, these types of information were ignored because the local community paid attention to recovering vital infrastructures. Although interviewers mentioned that the local community provided significant help, it was hard to get the clear quantity of investment and resources that were used in these areas.

(2) Regarding farms, agricultural work is periodical and timely. During the growth cycle, different works are needed in various growth stages to promise a real gain. Proper and immediate responses are critical to minimizing poorer quality crops for the year after flood events. Three types of work should be finished. First, save existing agricultural products. Secondly, recover the farm to a normal condition that is suitable for crop growth. Thirdly, replant products to decrease the loss of gain. To support these types of work, farms need machines, materials, and human resources. From the interview, farming faced some basic losses and recovery work: lost markets and lost produce, the replacement of equipment and fences; arable land losses, extra weed eradication, loss of particular crop and loss productivity of the soil for the next growing season (Jane Mullett 2015). The majority of these works rely on good transportation to get the farm recovered. Transportation does constrain the recovery of farming business. In this case, some of the immediate responses are to get agricultural products to market, replace vital farm equipment and returning equipment, such as irrigation equipment (pumps and pipes), back into position. During this period, the local community provided significant help. However, efforts were not well recorded. Different types of information are needed for this estimation:

(a) Detailed recovery plan and schedule for farming recovery (b) Summary of recovery resources, such as equipment, tech support, fences, etc. (c) Delay of delivery and recovery due to the bridge closure.

6.6.3.3 Opportunity costs of extra traveling time

Regarding opportunity costs of time, the first problem is to use proper values to estimate time. The time could be used for work, leisure, working out, etc. In this research, the opportunity costs of extra traveling time are calculated using salary. It is assumed that individuals would create at least the value of their average wage during these times. There are two salary standards for heavy vehicle drivers. The average salary in Brisbane, Queensland is 23 AUD/hour. For other bridge users, median payment is around 20 AUD/ hour (Salary Data & Career Research Center (Australia) 2016).

During a bridge recovery, losses would be different for different type of vehicles. When the bridge was closed to the public, all bridge users suffered delay of extra 20 minutes on average (15-25 min). After one side of the bridge was reopened to small vehicles, extra traveling time for light commercial and small vehicles was around 10 minutes. Therefore, the total opportunity costs of time were:

(1) During bridge closure time:

For heavy vehicles drivers: the loss was around 41,470.40 AUD

For small vehicle bridge users: the loss was around 100,018.80 AUD

(2) During one side open:

For heavy vehicle drivers: the loss in one year was 540,596 AUD

For small vehicles bridge users: The total loss was around 651,908.30 AUD

During bridge recovery period, the opportunity costs of extra time spent travelling were around 1,333,993.23 AUD.

6.6.4 Indirect intangible losses

This part discusses the observe intangible losses that would be incurred after bridge damage. Three phenomena would be discussed at this stage: residents show loss of trust in authorities, impacts on labour market change and unemployment and impacts on the environment from debris disposal. In this case, interview information that was collected by CRC groups would be used to describe situations after flood events and support further research in this area.

6.6.4.1 Loss trusts on authority

Loss of trust in authorities is a phenomenon that can also be observed during and after rehabilitation. After three flood events within 4 years, residents have deep knowledge of flood events. In this case, CRC (2016) groups interviewed local residents in Locker Valley to summarize their emotional changes:

(a) local residents show scepticism towards the design for the floodway.

(b) Some people challenged the speed limit on the road.

(c) Restoration help was provided to some people but not to others, leading to question of fairness.

All these phenomena are summarized in this research as the loss of trust in authorities. From the interview, communication and participation between the local community and residents seemed to play important roles. Local residents in this region showed a strong willingness to be involved in the recovery work. They believed that their experience and knowledge were essential to rehabilitation. However, three problems could be found in the interview for residents to be involved in rehabilitation. First of all, local residents said that at the community consultation meeting, they just revealed pre-existing plans rather than listening to the local community. Secondly, consultant sites were not efficient or effective. Some people believed that reception is not enough for people to get different answers and provide advice. They had nowhere to get proper answers. Others mentioned that the council had a site office to talk to individuals to solve their access issues. However, they believed that the consultant site, which had rigid criteria, was not so helpful. Thirdly, local residents believed that access was important to them, and they need a road system that was resilient to flood events. A cleared and quickly drivable road system was expected by residents. In this case, one area of damage after another on the road system may increase the suspicion on the governance of the local council.

After bridge damage, residents showed their dissatisfaction and scepticism on the recovery progress. During bridge recovery, it was important for the local community to publish recovery plan and progress to the public. Some complaints that can be summarized from reports pointed out expectations and trust of bridge users would change when they doubt bridge recovery. First of all, residents claimed that the local council should take their opinions seriously. Secondly, common views from bridge users believed that there should be hearings and meetings to improve information transparency. The public expected more information about detailed recovery plan rather than simple decision and conlcusion that are made by the local council. In this case study, local residents showed their strong willingness to be involved and to participated in recovery activity. However, the performance and reaction of the local council let them down. Another particular type of feeling mentioned here is the fairness problem. After flood events, some of the inhabitants accepted more help from the local council, while others did not due to road recovery progress and accessibility.

A review of Australian recovery policy clearly indicates that reovery efforts which focus on vitims of natural disaters must be timely (in that assistance is provided when it is needed and for as long as it is needed), proactive (being actively involved in planning for a range of options) and accessible (developing creative strategies to ensure people are able to receive assistance) (Winkworth 2007). In this case, loss of authority is believed related to these three points. The local council makes lots of efforts on information disclosure, providing help, involve local residents in post-disaster recovery. However, these efforts and works cannot meed the expectation of bridge users.

From the short summary of the interview (Salary Data & Career Research Center (Australia) 2016), two considerations should be noticed: On the one hand, residents admitted that the local council provided significant help to community recovery. On the other hand, local residents were not satisfied with what had been done by the local council. In this case, there were many concerns that caused the lost of residents' trust in the local council. Communication, coordination and information transparency should be further discussed for their impacts on misunderstanding and trust crisis during bridge rehabilitation. Establishing trust between the local council and the community after flood events could be another big issue during rehabilitation.

6.6.4.2 Change of labour market

After flood events, unemployment is another phenomenon that should be concerned. From previous research, regional employment decreased by 3.4% level on average after flood events (Sarmiento 2007). It was claimed that access and bridge availability would play a major role in increasing unemployment. In this case, there were three main types of job loss (Jane Mullett 2015):

(1) Loss of employment due to the inability of getting to work. (2) Some workers had to find places to stay outside of the Lockyer Valley as they were unable to get in and out to work. (3) Pickers and farm workers lost their jobs temporarily when they could not access farms. There is no specific survey to address the problem of how many people believe that they lost their jobs temporarily or permanently due to a loss of access caused by bridge damage.

In this research, there is no specific data to illustate the population that lose their job due to bridge damage.

During bridge recovery, there would be job opportunities that can be provided for local communication. Jobs that were related to construction work were provided. That could benefit the local labour market. Around 1,800,000 AUD were spent on bridge recovery in 2011-2012. This money was transferred into workers' salaries and profits to construction-related business. Despite constuction-related work, there were also some other temporary job opportunities, for example, reception in temporary consultant sites to solve travel problems of local inhabitants. Both local inhabitants and businesses were involved in earning money from the bridge recovery costs.

However, not all the job opportunities were given to local inhabitants. There were not enough certified construction workers in the local communities. Some of the workers that were involved in bridge recovery came from other towns and valleys. The bridge designer for the recovery came from outside of the local community. In Lockyer Valley, some of the repair works were delayed due to a lack of workers. Construction companies would focus on the main road, and then would repair some rural paths. The consequence is that some types of workers would still be short, whereas some people would lose their jobs. This requires further tracing of the labor market change.

Three regional employment and job reports are conducted between 2012 and 2013. Two of them summrized the employment change in recent years in Lockyer Valley region (lawrence Consulting 2013; The Stafford Group 2013). The other one summrized the demand of qualified works in the Lockyer Valley (The Office of Regional Education 2012). All three reports cannot provide detailed information about consequences that were brought by the 2011 flood event. In addition, these reports did not summarize the employment and unemployment population due to the disruption of bridge and road infrastructure.

6.6.4.3 Intangible impact on environment

This part concerns the environmental consequences that are caused by debris that was created during bridge recovery, including debris and construction wastes. It is an intangible cost that is always ignored by the public. To estimate intangible impacts on the surrounding environment, four aspects should be measured: greenhouse gas emissions, other harmful gas emissions, leachate, and amenities. According to the Australian government, impacts can be measured by costs that are used to minimize negative impacts. Refering to the costs in Table 5.7, the average cost is around 11 AUD, which is summarized from debris disposal costs. Refer to chapter 6.1, debris quantity disposed is around 13.5 tonnes.

To sum up impacts of 13.5 tonnes of debris, the total costs due to the impacts on the surrounding environment would be 148.5 AUD.

CHAPTER7 Conclusions, Contributions, and Implications

7.1 Introduction

This research reviewed the up to date research on economic impacts of natural disasters, flood events, and road infrastructure in Chapter 1 and Chapter 2. There are still knowledge gaps on economic impacts of the bridge collapse in flood events. In Chapter 1, challenges are summarized for a developed proper approach to solve some questions in this area. In Chapter 3, the methodology explains how to approach three research objectives. Chapter 4 discusses how to use current knowledge to identify and categorize economic losses that are caused by a bridge collapse in a flood event. A causes and effects analysis help distinguish direct and indirect impacts that are caused by bridge damage. In Chapter 5, existing models are used to quantify and describe different types of economic losses. In Chapter 6, a case study is used to illustrate the integrated models.

This chapter summarizes previous discussions and efforts made on economic impacts of a damaged bridge in flood events. In section 7.2, it concludes that conditions of three objectives in this research. The third section introduces the main contributions to current knowledge. Section 4 discusses implications to research and local community. In section 5, the main constraints and limitations of this research are described. In section 6, there would be some recommendations for further research in this area. Section 7 will summarize this whole research and give an outlook for future studies.

7.2 Conclusions regarding objectives

The objectives of this research are:

(1) Identify economic impacts of bridge damage in flood events on the local council/community

(2) Categorize economic impacts systematically and distinguish them into direct/indirect and tangible/intangible
(3) Identify a proper model to measure the tangible losses and interpret the intangible losses properly
(4) Demonstrate the integrating model in a case study

The first objective of this research is to understand the economic impacts that are caused by bridge damage after flood events. This research systematically summarizes different types of losses that are related to bridge damage from previous studies. For the second research objective, all economic impacts are classified into four types. In addtition, a matrix is introduced to help categorization. The third objective is to apply multiple models to estimate the economic impacts that are summarized in this research. These models would include damage repair costs, debris clearance costs, detouring costs, prediction of decreasing productive capacity due to bridge damage, the value of historical buildings and environment impacts that are caused by debris clearance. The fourth objective is to apply available data that was collected from the Kapernicks Bridge to demonstrate integrated models.

7.2.1 Objective 1: Impacts identification

Accessibility of the bridge is important to stakeholders. Access provides significant economic benefits to the surrounding areas and bridge users. Each time of a bridge closure would create a large inconvenience and economic losses. Identifying and understanding the economic impacts is the first step to estimate gross losses due to bridge damage. Moreover, a systematically study on the economic impact of bridge damage could help the local community and stakeholders to understand their losses due to bridge damage after flood events. With acknowledgement of economic impacts, local community and stakeholders can make a fully pre-disaster plan and preparation to avoid or relief predictable losses in high flood frequency areas.

This research takes the bridge as the research object and concerns both the bridge’s asset value and the value of accessibility. The bridge is an essential road infrastructure with massive construction investment. Its safety and reliability are also important to public safety concern. After flood events, repair of different structure components would need to be carefully designed. It may take a longer time than expected. Repairing the bridge would include post-disaster inspection, design, examine and approve, fund preparation, and construction. During a bridge recovery, there will be different ripple effects caused by the transportation problems. Stakeholders need to understand these economic impacts so that they can estimate their losses.

The process of bridge recovery can impact the recovery of associated facilities, such as, sewers, power supply, internet, etc. In this research, associated facilities are considered as one part of productive conditions. Without enough productive conditions, industries cannot maintain their daily production. Supplies and demands of industries create parameters with which to estimate the post-disaster productive capacity of local industries.

Impact identification reveals gross losses from different social sectors. There would be different victims: the local council needs to pay for bridge recovery. In addition, the local council would also need to prepare for traffic control, support to bridge users, communication with stakeholders, etc. For stakeholders, the detour would be first problem that follows the bridge damage. Stakeholders would suffer traveling challenges and losses.

There are also some industries that get benefits during bridge recovery. Some construction-related businesses, such as local building businesses and quarry businesses are more profitable during bridge recovery. In this research, these benefits are described as providing job opportunities to labour markets. Only small groups of trained workers can benefit from job opportunities. The common condition is that the unemployment rate would increase in flood-affected regions.

Objective1 would be a good foundation for estimating the economic impacts of bridge damage. Moreover, economic impacts would show the importance of a bridge in regional road networks and other types of infrastructures. Stakeholders of the bridge could introduce a pre-disaster plan and preparation to decrease their loss in the future.

7.2.2 Objective 2: Impacts classification

The second purpose of this research is to classify different types of economic impacts properly. Analysis and category as detailed discussed in Chapter 4. This part classifies all economic impacts into four groups by introducing four concepts, direct/indirect and tangible/intangible. Interestingly, different institutions, organisations, and research have different perceptions of direct/indirect economic impacts. In some research, business disruption is considered as directly caused by natural disasters. Some would consider business as the consequences of transportation problems, lack of productive conditions, workers, and industry damage after natural disasters. Others introduced the business interruption as a stand along category (Hallegatte & Przyluski 2010). The differences are mainly caused by their research purpose and models that would be applied. In this research, the bridge would create secondary effects on local business and industry by cutting off the connection and necessary services. It is indirect losses.

To clarify relations between different economic impacts and bridge damage, causes and effects are also discussed in this research. It reveals relations of different economic losses and summarizes reasons that would lead to economic losses.

The summary of different economic impacts illustrates relationships between different types of economic impact. It sets up foundations for model development of our model and future investigations.

7.2.3 Objective 3: Model Development

Objective three is related to the research question metioned in chapter 1, “Identify proper model to measure the tangible losses and interpret the intangible losses properly.” Models are discussed and introduced in Chapter 5.

Concepts such as damaged states and performance groups are introduced and applied in this chapter to help accurately evaluate bridge damage. These concepts can significantly improve the accuracy and operability of estimations. Performance groups can effectively prevent double counts (Mackie, Kevin Rory, Wong & Stojadinovic 2008). In addition, damage states can be aligned with further research on repairing methods, repairing quantities and predicting time limit of the project. Future research should be conducted into more meaningful assessment with groups of structural components. Analysing the strength of a whole column would be more useful and meaningful than focusing on individual spiral deformations. It is believed that damage states and performance groups could improve estimation of bridge repair costs on accuracy and operability.

For tangible losses, they can be measured by market value. This part discusses the costs of debris clearance and disposal, bridge repair and recovery, extra travel distance, extra travel and reduced productive capacity of the industries. In this part, models would focus on two aspects: The first part would estimate the damage states of the bridges. Accurate judgement and evaluation of bridge damage would be significant to quantities and repair methods. Based on damage states, further prediction of the time limit of repair and repair costs would be possible. The second part would concentrate on analysing road networks and routine choice after bridge damage. It is significant to add data as detailed as possible into the regional map system to make an appropriate judgement of post-disaster traffic conditions and detour routines. It is the foundation for further estimation of extra traveling, additional traveling time, and decreasing productive capacity.

The tangible economic loss is the main part that allows stakeholders of the bridge to estimate economic losses due to bridge damage. In addition, it is important evidence for making a strategy for pre-disaster preparation and post-disaster recovery.

For intangible losses, there is no recognized method to measure different types of intangible losses. In this part, the researchers would like to interpret the economic impacts and propose to collect valuable data for future research on these areas. For different types of economic impacts, different recommendations are introduced. For historical bridges, the value of heritage that is based on willing-to-pay methods would be derived from Heritage Chairs and Officials of Australia and New Zealand. Also, descriptive data could also be available in local council and heritage offices. For the psychological part such as the psychological impacts of bridge users and losing trust in authorities, this research would like to collect information about efforts that are made by the local council to relieve negative psychological implications.

In terms of intangible losses, surveys and interviews in these areas are recommended. In this area, the main concerns of the local council are supporting bridge users, maintaining their authority and understanding unemployment after flood events.

The significant finding regarding model development that would impact the choice of model is that lots of current models are not validated and justified. There are two main reasons: The first reason is that results, which are derived from different models, show significant differences. It is hard to justify which model would be more accurate than any other model. For most of the computable general equilibrium (CGE) models, results would be lower than input-output (I-O) models. It is believed that CGE models would overestimate the function of markets. Economic losses would be underestimated. For I-O models, there is a lack of flexibility. The I-O model is based on rigid relations between inputs and outputs. That would lead to overestimation. Another reason that would limit model validation is that the research could not collect enough detailed and appropriate data on disaster cases. For disaster research, first-hand data seems to be important. However, many studies were set up without appropriate cases to collect first-hand data. In the process of selecting models, two constraints should be considered. Models should balance underestimation and overestimation conditions. Otherwise, data for the model would be easy to derive. The choice of model would be based on the best judgement and knowledge of the researcher.

7.2.4 Objective 4: Case study

Objective 4 refers to research question four, which states “demonstrate models in case study.” This part is clearly discussed in chapter 6 using current knowledge and data.

In this case study, the researcher used current data, which was collected during 2011 flood events, to demonstrate the models. By applying integrated models, shortages and constraints of current models can be identified.

The first finding of this part is that current disaster records that are collected by local councils are not sufficient to fully demonstrate this integrated model. For further research on natural disasters, improved data contents are necessary and important.

The second finding is that the integrated model may still be complex to the public. It has high requirement of data collection. In addition, it needs professional knowledge on construction areas. Moreover, regional map establishment and alternative road choices would require extensive work.

However, local councils and stakeholders of the bridge can still get benefits from the case study. This case study can be used as a guide for them. They can modify parameters to regional data and estimate economic losses. The local council would collect more related data to support estimation, and these data would benefit future research.

7.3 Contributions to the Academic Knowledge Base

This research would contribute to the current knowledge on three aspects:

(1) Improve the understanding of economic impacts that are caused by bridge damage in a flood event. Before this study, few specific investigations discuss economic impacts that are caused by bridge damage after flood events. This research reviews previous works and

interviews to summarize related economic losses. This research would set the foundation for further research on this area.

(2) Applying and integrating existing model to estimate or describe different types of economic impacts. This research reviews different types of models that were implemented in different areas to estimate economic impacts that are caused by bridge damage in flood events. Integrated model has significant meanings to victims due to bridge damage. This model allow victims who are usually the primary stakeholderso fthe bridge to estiamte their losses. In addition, this model would also contribute to other areas. For example, it can provide evidence for the local council and other related organisations to conduct pre-disaster preparation, and implement quick response plans and post-disaster recovery strategies.

(3) Demonstrating the models in the case study can help identify its current knowledge gaps and shortcomings. In this research, the integrated models are applied to estimate economic losses of Kapernicks bridge damage. This part points out current shortages of data collection and recoreds. there is a gap between data collection and data needs. To improve data accumulation, time limitations of data and proposal for data collection are discussed in this research. In addition, this part can be treated as a guide for local councils to estimate economic losses. They can follow the steps laid out here and modify parameters to estimate regional losses.

7.4 Implications in Practice

The introduction and literature review reveal that Australia is a flood-vulnerable country. Flood distribution and road distribution maps illustrate that road infrastructure, including bridges, is also vulnerable. In flood events, bridge damage would lead to different types of economic problems. This research would be set up to explore and estimate these economic impacts. There would be different groups of individuals and organisations who would get benefits from practices of this method.

1. Local council and stakeholders of bridges

The first purpose of this research is to help the local community and local council understand economic impacts, and estimate losses due to bridge damage in flood events. This research systematically discusses economic losses that would happen due to bridge damage in flood events. The majority of these economic losses would not be measured and included by insurance. Local councils and stakeholders of the bridge would clearly understand what losses they need to face to during bridge closure and repair.

Noticing significant economic losses due to the bridge damage could help local councils and stakeholders prepare for some predictable losses. For example, the local council could prepare temporary facilities to maintain traffic after bridge damage. Also, the local council can also provide help to most vulnerable residents and industries.

With a better understanding of reasons for economic impacts, a targeted strategy could be applied. In this research, a loss of authority is identified. It is believed that the main reasons are insufficient communication between the local community and the local council, the information transparency of the recovery plan, and rejecting the participation of residents. The local council could take more measures to minimize negative impressions during bridge recovery.

2. Implications for researchers

This research sums up current knowledge on the economic impacts of bridge damage that are caused by flood events and how to estimate these economic impacts. Before this research, there was limited research focus on this area. This research provides the foundation for future studies to improve the accuracy of economic estimation. In addition, this research would benefit future research on preparation, post-disasters recovery, and improving the resilience to disasters.

7.5 Study limitations

This section would consider the limitations of this research in different aspects. There are knowledge gaps in the research methodology, model choice, and data collections.

1. Methodology

Economic impacts identification mainly based on a literature review, interview materials, and reports. This research are conducted by summarizing, analysing, and judging economic impacts that are mentioned in previous studies. However, there are still fewer previous studies related to bridge damage and flood events. Economic impacts that are caused by bridge closure and damage have also been explored less. Some previous research identified economic impact due to the knowledge and experiences of researchers and practitioners. Some of their opinions are not justified properly. The researcher believes that a lack of comprehensive studies, interviews, data, and justification would constrain the process of fully identifying economic impacts in this research.

2. Model choice

The selection of the model used in this research is limited by the best judgement of the researcher. Choice-making is based on literature review and the best judgement that researcher can make. However, there would be more accurate and appropriate models that would be developed in this area in the future.

Research on natural disasters and their economic impacts are still in the early stage. Results from different models would vary a lot. In this research, models only reflect results due to current knowledge on economic estimations. There are limitations of model selection. During selecting proper models, the researcher preferred available and validated models rather than any other reasons. Currently, lots of models that are developed for economic estimations still cannot be validated due to data constraints and knowledge gaps (Merz et al. 2010). These models have potential to be more accurate or more appropriate when they are validated and improved.

Some models has obvious limit that will constrain the integreted model. In measuring bridge repair costs, not all types of bridges can be described by validated damage states and performance groups. That will limit the applied range of integrated model.

3. Data collection

Data collection would be one of main constraints that impacts the case study part of this research. Sufficient, reliable, and detailed data are still required to meet the demands of model. Although local councils and agents provided a lot of help with data collection, the author could not obtain all the data required to test out the integrated model.

For damage states estimation, the first inspection and repair plans are not available due to data collection issues. In addition, there are flood events in 2008, 2011, and 2013. New damage were brought to The Lockyer Valley region when this region was not completely get recoverd. Damage records and interview would be impacted by continuous damage in this region.

Dozens of photo were taken after the 2011 flood events. However, the pictures were taken by different residents and institutions from a great distance and were not suitable for research purpose as they did not display the damage in detail. Therefore, the value of these photos is limited.

In addition, some relevant data were not collected on time. In order to continue this case study, some necessary information are derived from other studies, reports, and institutions outside of the case study region.

7.6 Recommendations for future Research

This research makes contributions to two areas of the current knowledge: It reviews current studies to identify and summarize the economic impacts of bridge damage caused by flood events and improves the current understanding of the economic imapcts of natural disasters. Also, this research applies existing models to help estimate these economic impacts. Different models are integrated to estimate the economic losses of a bridge's stakeholder. For understanding the economic impacts of natural disasters, current research is still at the very beginning stage to estimate impacts that are caused by natural disasters. This research can provides some suggestions for future studies. All Suggestiongs are related to this research topic. Some of these studies could be finished in the short term. However, some would need long-term efforts.

1. There is still a knowledge gap to align the parameters of flood events with bridge damage states and debris quantities. Parameters could be depths, flow velocity, flood duration, etc. Some research relies on empirical data to predict damage conditions. Others try to apply dynamic parameters to predict damage in flood events. However, the accuracy of existing models in this area is concerned. Future research could focus on improving the accuracy of previous research or applying new methods to estimate bridge damage condition in flood events. This type of research would be important to economic impacts estimations, post-disaster recovery, disaster relief, and preparing and improving resilience after disaster events.

2. Long-term tracking of a disasters-impacted region is still needed. After a disaster, different valuable studies could be conducted and validated. For example, surveys and interviews can be conducted. Currently, lots of economic impacts are based on researchers' experience and knowledge. Long-term tracking of disaster events could confirm their findings, validate their models or expose their flaws. At present, there are lots of models could not be validated. Tracking disaster events can provide an excellent opportunity to validate and improve existing models. In addition, long-term tracking could provide meaningful and reliable data for future research. Data are

currently another barrier to research. Tracking disaster events could provide lots of reliable and detailed data.

3. Researchers could also focus on improving the resilience of local communities in a disasters vulnerable region. Australia is a flood-vulnerable country. There are lots of local communities need professional knowledge on improving the resilience of local community in natural hazards. For example, Locker Valley suffered three floods in five years. Improving resilience in this region to decrease economic losses and quickly recover from disaster events is important to the victims.

4. In this research, losing trust in local authorities could be a further research topic. After disasters, interviews showed that residents challenge the decisions, plans, and recovery work of the local council. The local government could lose its authorities. Currently, loss of authority is considered as a consequence of insufficient communication between the local community and the local council, information transparency of the recovery plan, and participation in recovery activity. Future studies could be conducted qualitatively to explore the main causes and effects of trust loss. It is also important to take active measures to minimize loss of trust during post-disaster rehabilitation.

For future research, there are still many topics and directions that need to be explored. Each area would be important to understand, estimate and relieve the impacts of natural disasters.

7.7 Closure

This is fundamental research on exploring the economic impacts of bridge damage. It contributes to the current knowledge in three areas. Firstly, it summarizes economic impacts that are caused by bridge damage in a flood event. This improves current knowledge on understanding how bridge collapses impact stakeholders and lead to economic impacts. All economic impacts are categorized into four groups. The second contribution is that existing models are introduced to estimate these losses. It allows the stakeholders of the bridge to estimate their economic losses due to bridge damage by applying related models. The third one is that a case study would also be used to demonstrate the integrated models. By applying the integrated model, a case study can illustrate the current knowledge gap, data limitation and model constraints on disaster studies.

This research would be an initial approach to understand, recognize and estimate economic losses from bridge collapse during flood events. It is only a small part of research on natural disasters. There are still huge knowledge gaps in understanding, predicting and estimating natural disasters and their consequences. To further understand about natural disasters, continuous tracking and recording of disaster events and their impacts on different areas are quite important.

Currently, more organisations and institutions are carrying out research on natural disasters. This research is a valuable attempt to estimate economic losses that are caused by bridge damage in flood events. It points out shortages and knowledge gaps for current research. New and current directions are identified for exploring economic impacts of disaster events. It provides foundation and guidance for future research.

CHAPTER8 APPENDIX

There is no fixed plan and method to repair a damaged bridge. Bridge repair would need to concern strength and safety of bridge structure components under forces and stress. However, there would be other factors that would impact repair methods. Repair plan would change due to damage states, force distribution and analysis, bridge condition, traffic volumn, etc. In addition, designer would make different judgement by their experience and knowledgement. Table 8.1 provides some common methods that are used to deal with brdige damages. Methods to quantify quantities of repair work are recommended.

Table 8.1 Damage states and estimation recommendation

Performance group	Damage states		Repair recommendations	Quantities	Units
Column	Concrete	Ds 1	No repair		
		Ds 2	Seal cracks and minor removal and patching of concrete		
			Epoxy inject cracks	2 × column height	LF
			Repair minor spalls	10% × (surface area) × (cover + 1’’)	CY
		Ds 3	Seal cracks, major patching		
			Epoxy inject cracks	4 × (column height)	LF
			Repair minor spalls	25% × (surface area) × (cover + 1’’)	CY
		Ds 4	The repair action is column replacement		
			Structural concrete, bridge	Gross column volume = (column height ×	CY

				(column diameter)	
			Bar reinforcing steel, bridge	(column gross volume) × (rebar weight estimate based on BDA 11-5)	LB
			Temporary support, bridge	Tributary length × (deck width)	SF
			Structure excavation	3’ embedment + 4’ concentric circle around column	CY
			Structure backfill	Same as structure excavation	CY
Column	Reinforcement	Ds 1			
		Ds 2	Replace buckled reinforcement, install steel column casing, excavate and backfill where necessary		
			Column steel casing	Steel casing volume calculated using: Outside diameter = (column diameter) +4’’, and thickness = 0.25’’	LB
			Bar reinforcing steel, bridge	5% × (total rebar weight)	LB
			Temporary support	1/2 Tributary length × (deck width)	SF
			Structure excavation	2’ embedment + 4’ concentric circle around column	CY
			Structure backfill	Same as structure excavation	CY
		Ds 3	Re-center column		s
			Re-center column	Depends on recovery plan	EA
		Ds 4	Same with replace		
Deck	Ds1		Clean deck for methacrylate	25% × (deck area)	SF
			Furnish methacrylate	25% × (deck	GAL

			area) / (90 SF/GAL)	
		Apply methacrylate	25% × (deck area)	SF
	Ds2	Epoxy inject cracks	50% × (deck length)	LF
		Clean deck for methacrylate	50% × (deck area)	SF
		Furnish methacrylate	50% × (deck area) / (90 SF/GAL)	GAL
		Apply methacrylate	50% × (deck area)	SF
Column foundation	Ds1	Add thresh hold		
	Ds2	Structure excavation	Volume = existing dimensions + 2 × spacing+ 2’ clearance	CY
		Structure backfill	Volume = new dimensions + 2’clearance	CY
		Temporary support, bridge	Volume of enlargement increased by (2 × spacing) in each dimension	SF
		Structural concrete, footing	105 kg/m3 × additional concrete volume	CY
		Bar reinforcing steel	(area of existing pile cap) / (4 dowels/SF) × (16’’ per dowel)	CY
		Drill and bond dowel	(area of existing pile cap) / (4 dowels/SF) × (16’’per dowel)	LF
		Furnish steel pipe pile	(No. piles) × (pile length)	LF
		Drive steel pipe pile	(No. piles)	EA
Abutment foundation	Ds1	Add pile threshold		
	Ds2	Structure excavation	Volume based on (existing dimensions) + 2 × spacing +2’clearance	CY
		Structure backfill	Volume based on	CY

<table>
<tr><td rowspan="9"></td><td rowspan="9"></td><td colspan="2"></td><td>(new dimensions) + 2’clearance</td><td></td></tr>
<tr><td colspan="2">Temporary support, bridge</td><td>Tributary area on either side</td><td>SF</td></tr>
<tr><td colspan="2">Structural concrete, bridge</td><td>Wing wall volume</td><td>CY</td></tr>
<tr><td colspan="2">Structural concrete, footing</td><td>Volume of enlarged foundation increased by (2 × spacing) in each dimension</td><td>CY</td></tr>
<tr><td colspan="2">Bar reinforcing steel, bridge</td><td>54 kg/m3 × (additional bridge concrete volume)</td><td>CY</td></tr>
<tr><td colspan="2">Bar reinforcing steel, footing</td><td>105 kg/m3 × (additional footing concrete volume)</td><td>CY</td></tr>
<tr><td colspan="2">Drill and bond dowel</td><td>(area of existing pile cap) / (4 dowels/SF) × (16’’ per dowel)</td><td>LF</td></tr>
<tr><td colspan="2">Furnish steel pipe pile</td><td>(No. piles) × (pile length)</td><td>LF</td></tr>
<tr><td colspan="2">Drive steel pipe pile</td><td>(No. piles)</td><td>EA</td></tr>
<tr><td rowspan="10">Abutment</td><td>Ds1</td><td colspan="2">Onset of repairable damage</td><td></td><td></td></tr>
<tr><td rowspan="5">Ds2</td><td colspan="3">Replace joint seal assembly</td><td></td></tr>
<tr><td colspan="2">Joint seal assembly</td><td>(deck width)</td><td>LF</td></tr>
<tr><td colspan="2">Structural concrete, bridge</td><td>(blockout volume) = 2 × (H × B × deck width)</td><td>CY</td></tr>
<tr><td colspan="2">Bar reinforcing steel, bridge</td><td>(blockout volume) × 48 kg/m3</td><td>LB</td></tr>
<tr><td colspan="2">Bridge removal, portion</td><td>(blockout volume)</td><td>CY</td></tr>
<tr><td rowspan="3">Ds3</td><td rowspan="3">Repair joint seal assembly</td><td>Joint seal assembly</td><td>(deck width)</td><td>LF</td></tr>
<tr><td>Structural concrete, bridge</td><td>(blockout volume) = 2 × (H × B × deck width)</td><td>CY</td></tr>
<tr><td>Bar reinforcing steel, bridge</td><td>(blockout volume) × 48 kg/m3</td><td>LB</td></tr>
</table>

			Bridge removal, portion	(blockout volume)	CY
		Repair back wall	Epoxy inject cracks	2 × (backwall height)	LF
			Repair minor spalls	10% × (back wall height) × (deck width)	SF
			Structure excavation	(deck width) × (deck depth) × 1’	CY
			Structure backfill	(deck width) × (deck depth) × 1’	CY
	Ds4	Replace joint seal assembly	Joint seal assembly	(deck width)	LF
			Structural concrete, bridge	(blockout volume) = 2 × (H × B × deck width)	CY
			Bar reinforcing steel, bridge	(blockout volume) × 48 kg/m3	LB
			Bridge removal, portion	(blockout volume)	CY
		Replace back wall	Structural concrete, bridge	(back wall volume) × 54 kg/m3	CY
			Bar reinforcing steel, bridge		LB
			Structure excavation	(deck width) × (deck depth) × 4’	CY
			Structure backfill	(deck width) × (deck depth) × 4’	CY
			Bridge removal, portion	(back wall volume)	CY
		Replace approach slab	Structural concrete, approach slab	(approach slab volume)	CY
			Aggregate base, approach slab	1/2 × (settlement due to 1/62.5 gradient) × (approach slab area)	CY
			Approach slab	(approach slab volume)	CY

		removal		
Approach Roads	Ds1	Onset of pavement problems		
	Ds2	Asphalt concrete	(vertical settlement) × (approach slab area)	TON
	Ds3	Asphalt concrete	(vertical settlement) × (approach slab area)	TON
		Excavation and backfill	(deck width + 6’) × deck depth × (thickness + 1’)	CY
	Ds4	Asphalt concrete	(vertical settlement) × (approach slab area)	TON
		Excavation and backfill	(deck width + 6’) × deck depth × (thickness + 1’)	CY
		Stemming operation	Depth × width× length	

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